Chasing the Unicorn: RHIC and the QGP

Unicorn = fantastic and mythical beast!

RHIC = Relativistic Heavy Ion Collider @ Brookhaven Natl. Lab (BNL):
collide large nuclei at high energies (also: SPS & LHC @ CERN)

QGP = Quark Gluon Plasma =
New *state* of hadronic matter, in
thermodynamic *equilibrium* at temperature $T \neq 0$

Q: Has RHIC made the QGP?

1. QCD @ nonzero temp.: the QGP
2. The QGP on the Lattice: numerical "experiment"
3. Experiments at RHIC: evidence for "gluon stuff" -
   the (high-pt) tail wags the (low-pt) body of the Unicorn

A: *Some* new *kind* of matter has been created

Quark Model: Particle Zoo. Masses, Scales....

Hadronic particles = strongly interacting = *baryons & mesons*

baryons: proton & neutron: mass = 940 MeV (MeV = 10^6 eV) ≈ 1 GeV

mesons: pions, $\pi^{\pm}, \pi^0$ mass π ≈ 140 MeV

All hadrons interact by pion exchange => fund. length: 1/m_π = 1 fermi (fm)
fund. time scale = 1 fm/c

Less familiar: strange baryons: Λ (1120), Σ (1190), Ω (1680)
strange mesons: 4 Kaons ($K^{\pm}, K^0, \overline{K}^0$) (540) & η (550) (η'(980)?)

Above: mesons spin 0, baryon's spin 1/2.
Also: spin 1 mesons: not strange, ρ (770), and strange ϕ (1120).

Ignore heavier particles, such as J/Ψ, Υ...

Quark Model: *all* hadrons composed of quarks.

Quark Zoo: 2, 3, 5(!) quarks

Above hadrons: from up, down, & strange quarks = u, d & s: 3 quark *flavors*
(Heavier flavors: charm, bottom, & top quarks)

π, K, η *very* light = (approx.) "spin waves" of (approx.) *chiral symmetry*
mass u&d (5,10 MeV) << mass s quark (100 MeV)

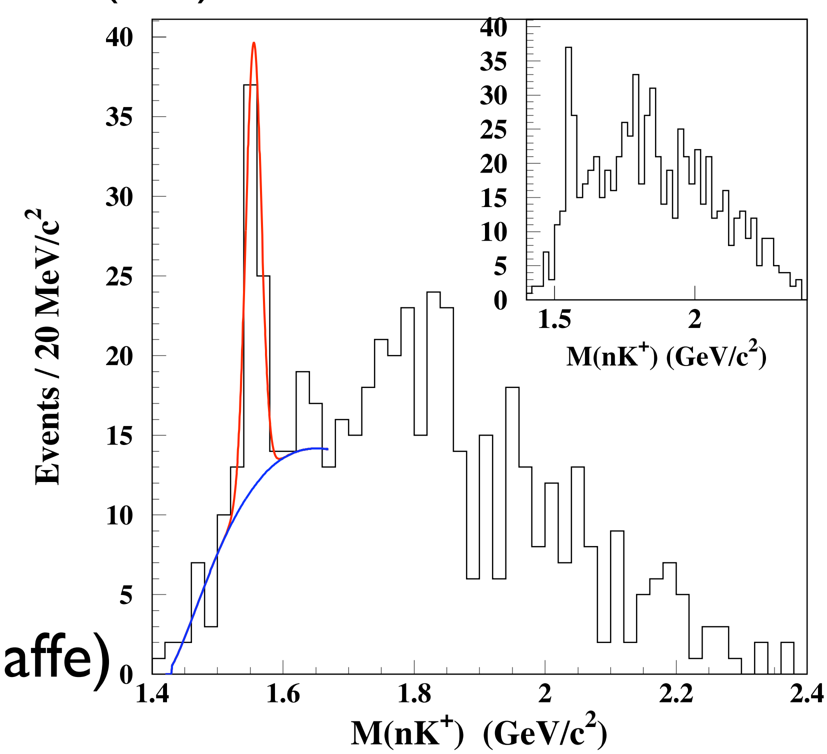
mesons = $\overline{q}q$ q = u, d, or s quark. π = u&d K = (u or d) & s

baryons = qqq N = u,d's; Λ = 2(u,d)&s; Σ = (u,d)& ss; Ω = sss.

New: "penta-quarks" = $qqqq\overline{q}$

Θ^+ = $uudd\overline{s}$ (Diakonov, Petrov, Polyakov)

CLAS @ JLAB: mass = 1150 ± 10 MeV. 8 σ!
width < 26 MeV! => *really* narrow



Where is the (hexa-quark) H-dibaryon=uuddss? (Jaffe)

QCD: Quark Model + *Gluons*

Global symmetries familiar. E.g., spherical symmetry = SO(3).
Uniform rotation everywhere the same in space.

Local symmetry: at *each* point, *independent* rotations in "internal" space.

Need new degrees of freedom: non-Abelian gauge fields = gluons.

QCD = SU(3) gluons + quarks. 3 of SU(3) = # colors.

Analogy: for critical point in *four* dimensions (= critical dim.), $\lambda \phi^4$ int.

$$\lambda(p) \sim \frac{1}{\log(\mu/p)}$$ p => 0

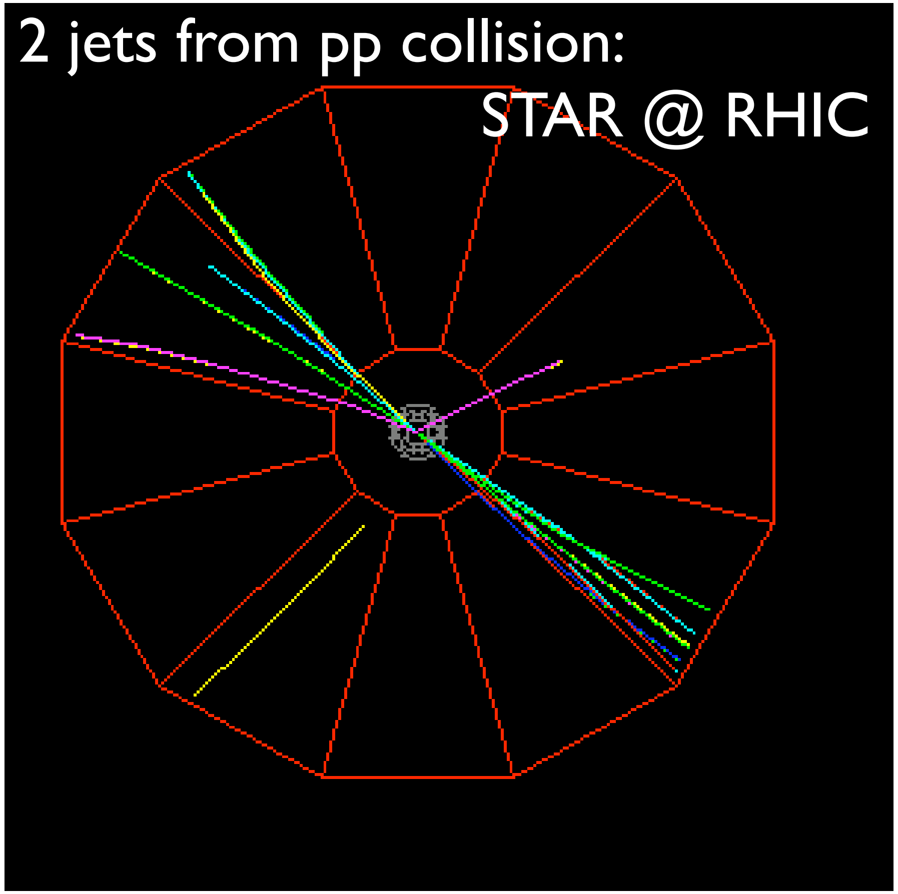
p = momentum, μ = ren. mass scale
=> compute in λ as p=>0, *large* distances

QCD = converse = *asymptotically free:* g^2 = QCD coupling constant

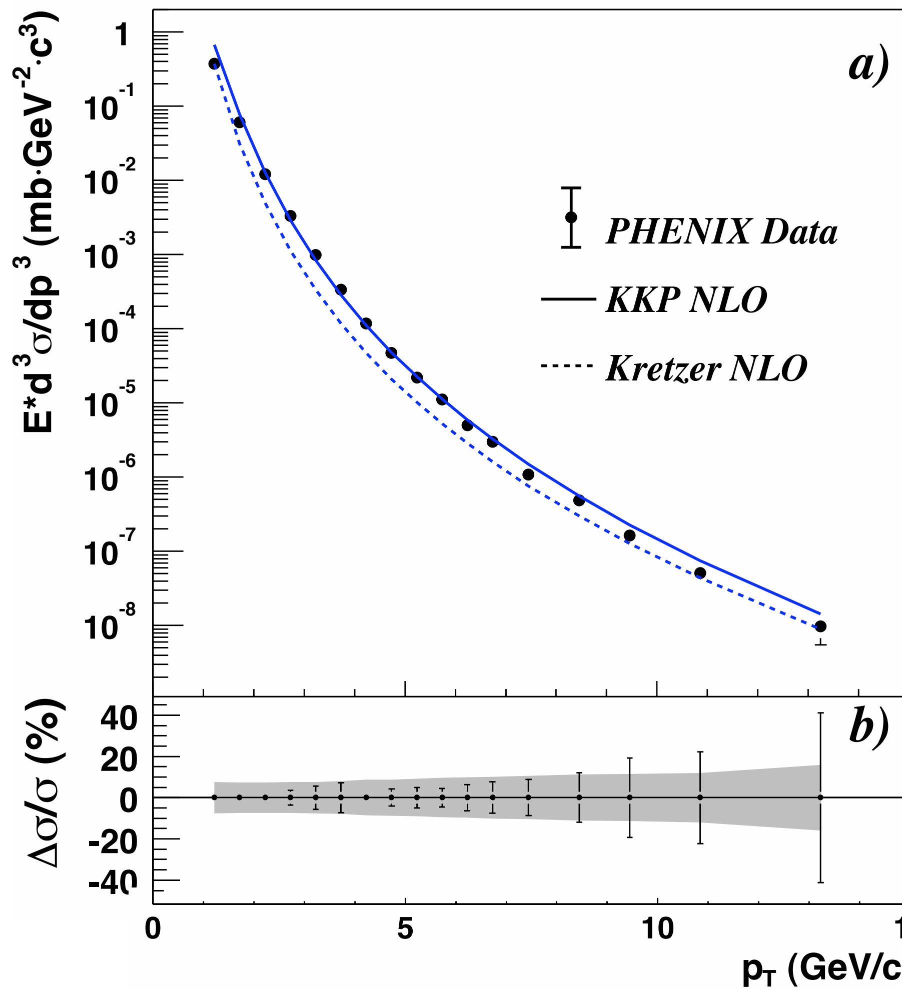
$$g^2(p) \sim \frac{1}{\log(p/\mu)}$$ p => ∞

=> compute in g^2 at large momentum
= *short distances*

Jets: "seeing" quarks and gluons in QCD



At high energies, energetic quarks and gluons produce jets. While rare, they are a striking feature. Note: by momentum conservation, any jet in one direction has a *backward* jet in the opposite direction.

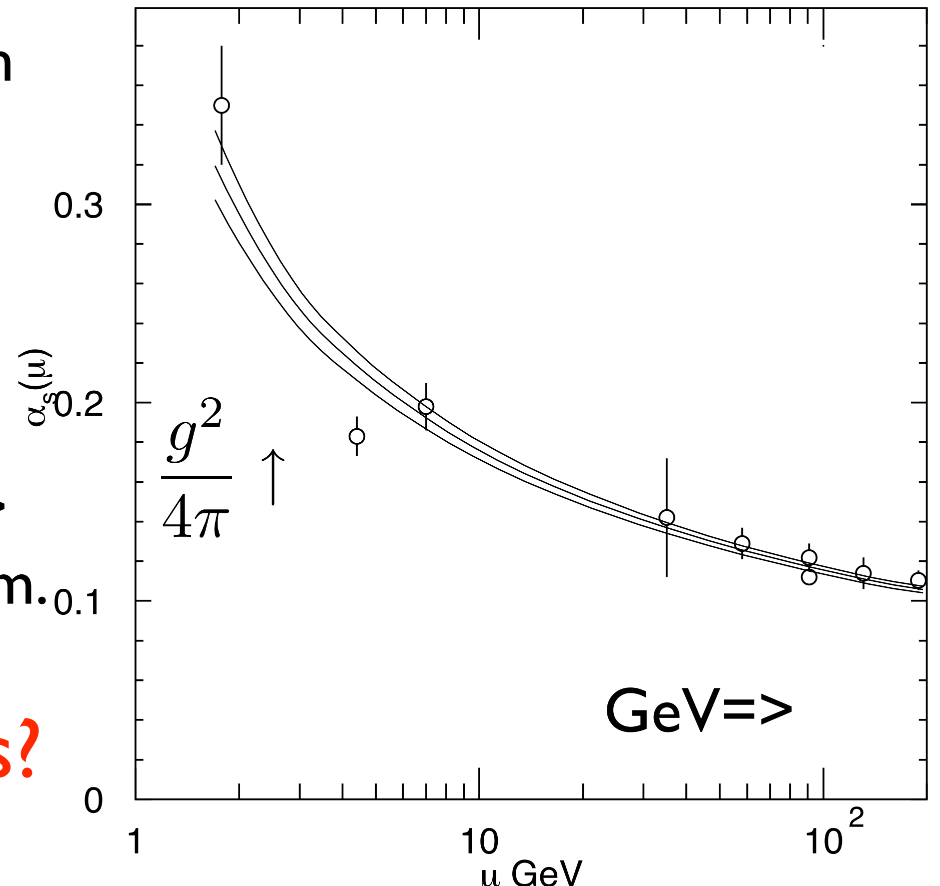


Jets can be reliably computed in perturbation theory, down to momenta ~ few (5, 50?) GeV!
At high energies, can tell, *indirectly*, between gluon jets & quark jets: on average, gluon jets are "fatter".

QCD @ Low Energies: Confinement

For a critical point at the critical dimension the coupling vanishes at small momentum, grows at large mom. ("Landau's ghost")

Conversely, in QCD, while the coupling is small at high momentum, it grows as the momentum decreases. To the right: => variation of QCD coupling with momentum.



What happens at large distances?

Confinement: quarks and gluons are *permanently* bound into color-neutral states = mesons and baryons.

"Infrared slavery": *linear* potential between quarks (more later)

Q: where are the states with pure glue = glueballs?

How to see the "glue" at *large* distances?

Symmetries of QCD: Chiral Symmetry

Most "familiar": chiral symmetry.

Like a magnet: *broken* at low temperature, restored at some finite temperature.
In broken phase, (approx.) "spin waves" = (almost massless) pions

up & down quarks: "flavor" symmetry = $SU_L(2) \times SU_R(2) = O(4)$

L(eft), R(ight) = chirality, *special* to massless fermions.

O(4) vector = $(\sigma, \vec{\pi})$. At zero temp, condensate: $\langle \sigma \rangle \sim \langle \overline{q} q \rangle \neq 0$

With strange quark, flavor symmetry = $SU_L(3) \times SU_R(3)$

$\langle \sigma \rangle \sim \langle \overline{q} q \rangle \neq 0$ => 3 π's, 4 K's, 1 η are massless. Correct # Goldstone bsns

(What about η' from extra axial U(1)? Instantons....
Could dramatically affect transition properties with *light* quarks.)

Deconfinement as a *Global* Z(3) Symmetry

't Hooft: rigorous order parameter for confinement .

Consider multiplying each quark by a constant phase:

$$q \to e^{2\pi i/3} q \quad , \quad \overline{q} \to e^{-2\pi i/3} \overline{q}$$

Mesons and baryons are invariant under this *global* transformation:

$$\overline{q} q \to \overline{q} q \quad , \quad qqq \to (e^{2\pi i/3})^3 qqq = qqq$$

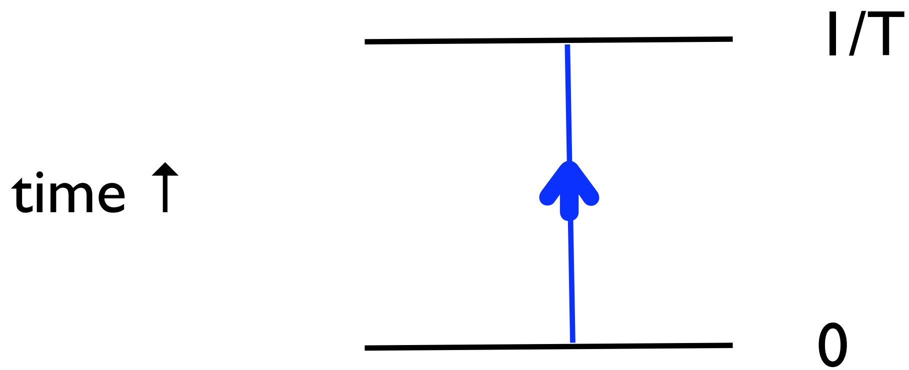
but any other states, such as q, qq, etc, are not. We could also use $e^{-2\pi i/3}$ as well, but only these transformations (and 1!) are allowed. This is a global symmetry of Z(3) (the third roots of unity).

Hence: confinement = *un*broken global symmetry of Z(3).

But! Only valid in a pure gauge theory, without dynamical quarks. These quarks above are "test" quarks. Dynamical quarks act as sources of Z(3) flux, and spoil the symmetry. In QCD, is the Z(3) symmetry approximate?

Test Quarks & Polyakov Loops

How to construct a test quark? Consider a nonzero temperature T: in imaginary time formalism, euclidean time runs from 0 to 1/T. Put an *infinitely* heavy quark down at some point in space: all it can do is run up in time:



While this test quark can't move, it *can* exchange *color* with the thermal bath. It does this through a (color) Aharonov-Bohm phase factor:

$$\ell = \frac{1}{3}\,\mathrm{tr}\,\mathcal{P}\exp\left(ig\int_0^{1/T} A_0\, d\tau\right)$$

= (trace of) propagator for test quark. Known as Polyakov loop, or trace of (thermal) Wilson line. (Wraps around in imaginary time => loop).

Deconfinement & Polyakov Loops

't Hooft: part of *local* SU(3) is *global* Z(3) (not obvious!) $\ell \to e^{2\pi i/3}\ell$

At T=0, confinement => quarks don't propagate => *UN*broken Z(3) symmetry

$$\langle \ell \rangle = 0 \ , \quad T < T_{deconf}$$

As T→∞, by *asymptotic freedom*, coupling g^2 is small, pert. thy. ok. So the global Z(3) symmetry is (spontaneously) *broken:*

$$\langle \ell \rangle \neq 0 \ , \quad T > T_{deconf}$$

Hence there is a temperature at which the loop gets a v.e.v.:

$T_d \equiv T_{deconf}$ = temperature for the *deconfining* phase transition.

Deconf. *opposite* to spins: Z(3) broken at *high*, and not *low*, temp.

In terms of order of the transition, just like typical Z(3) spins.

Order of Phase Transitions

Most cases follow from simple mean field analysis:

Deconfining transition: cubic invariant is Z(3) symmetric: ℓ^3
=> *first order deconfining trans.* (Svetitsky & Yaffe).

Chiral transition: for two massless flavors, O(4) sym. => *second order chiral trans*
For three massless flavors, $SU_L(3) \times SU_R(3)$ symmetry. Again, *cubic* invariant $\det(\Phi)$ => *first order chiral transition.*

Tech.'y: no restoration of axial U(1). Even if so, still *first order chiral transition*:
"fluctuation-induced" first order, like superconductor (RDP & Wilczek).

Guess: First Order Transition(s)?

"Of course"! Hadrons ≠ Quarks & Gluons.

But: relation between deconfining and chiral transitions? 1 or 2 transitions?
For QCD, *both* Z(3) and chiral symmetries are *approximate*.

The “Unicorn”:

Quark-Gluon Plasma =

Deconfined,
Chirally Symmetric “Phase”

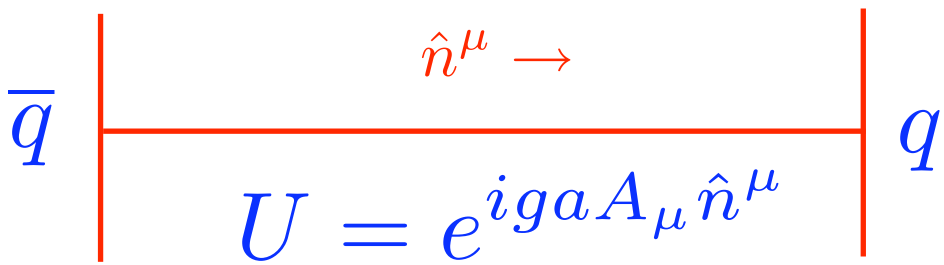
But how to compute
properties of the QGP?

QGP on the Lattice: "Numerical Experiment"

How to compute properties of transition = *strong* coupling regime?

Put theory on lattice! Then simulate numerically.

Wegner & Wilson: *easy* for *local* gauge theory: quarks on sites, gluons on links.



Lattice spacing = a. Asymptotic freedom => *unique* result for a=> 0 (p=>∞)

Example of universality: e.g., at 2nd order transition, over large distances,
critical exponents *unique* (func. of symmetry group & dimension)

Here, "dimensional transmutation":
once value of coupling is fixed at some scale, *nothing* left to fix.
All dimensionless ratios are *unique* (func. of symmetry group & dimension)

What the Lattice can do

But: how close is the lattice (today) to the continuum limit, a=0?

"Pure" gauge (no dynamical quarks): present methods close to a=0!

QCD: present methods *not* close to a=0. *All* results tentative.

Very hard to put *global* chiral symmetry on lattice!

View: lattice simulations as (another) experiment... What it has told us so far:

Pure gauge: pressure for *all* temp.'s. T_d ~ 270 ± 10 MeV.
Weakly first order deconfining trans.
Non-perturbative QGP from T_d => 3 T_d. NO "Of Course"

With quarks: T_c ~ 175 ± ? MeV
Order? Crossover today.
Only *one* transition (chiral = deconfining)
"Flavor independence": pressure with qks like that without qks.

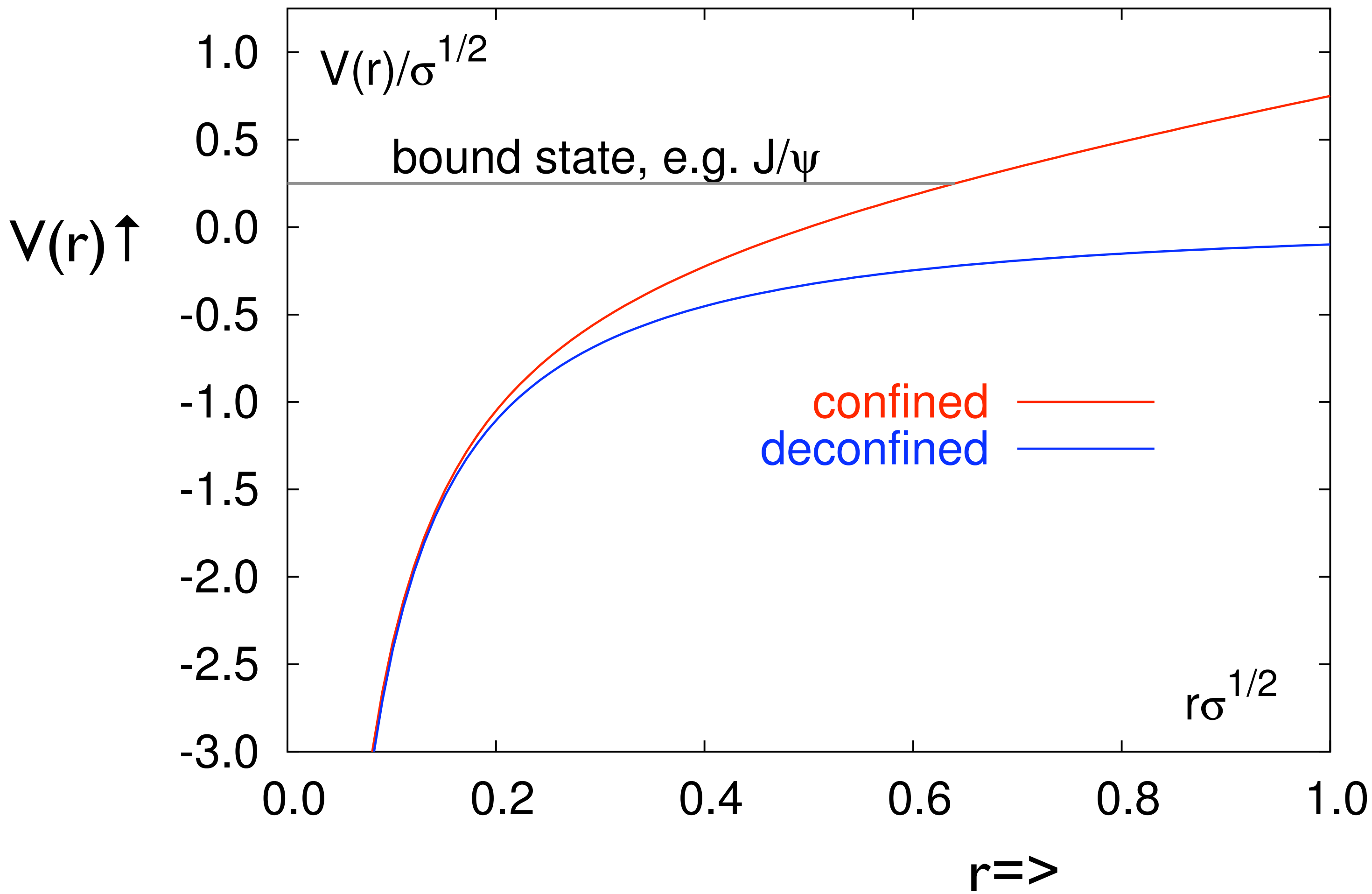
Confinement and the Quark Potential

T < T_c: V(r) = potential between test quark and anti-quark,

V(r) ~ σ r as r → ∞: σ = string tension.

Linearly rising potential => permanent confinement

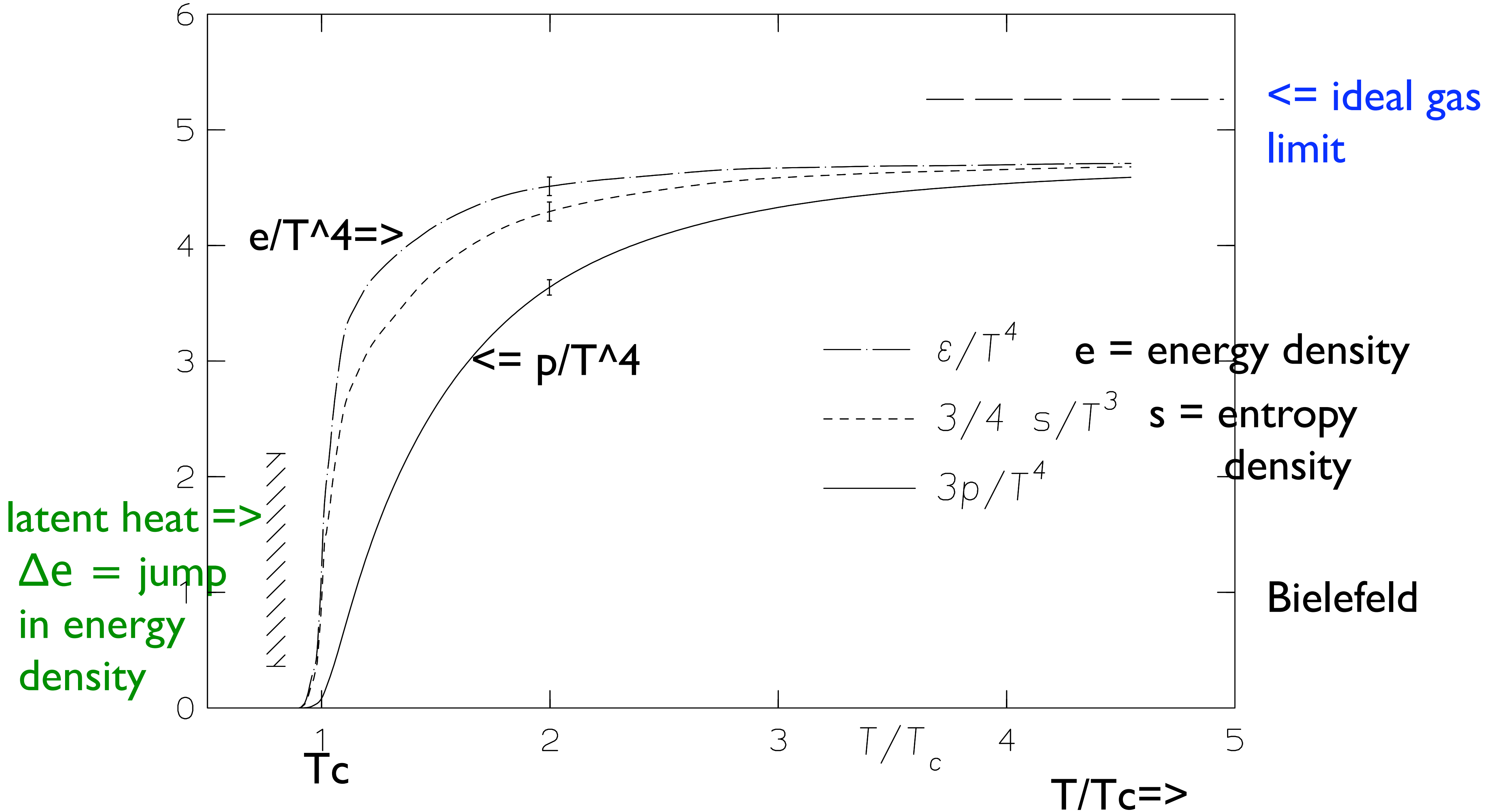
T > T_c: V(r) → *constant* as r → ∞. *Deconfinement.*



Lattice: "Pure" Gauge Thermo. for SU(3)

In *equilibrium*, everything follows from pressure $p=p(T)$ (T=temperature)

Asymptotic freedom => p/T^4 => constant as $T \to \infty$.



Lattice: "Pure" Gauge SU(3) Thermo.

Find: can extrapolate to continuum limit reliably.

Tc ~ 270 MeV ± 5 % (scale - and error! - dom.'d by string tension)

T<Tc, pressure *very* small in the confined phase.

Pure gauge => spectrum *massive* glueballs. Lightest glueball ~ 1.5 GeV

Pressure of *heavy* glueballs ~exp(-m/Tc) << 1 *very* small. Or: Tc small.

T → ∞: asymptotic freedom => p → *ideal* gas as T → ∞ $= 2 \times 8 \times \frac{\pi^2}{90} T^4$

T>Tc: relatively rapid approach to ideal gas: ~80% ideal gas by 3 Tc.

Suggests: *non*-perturbative behavior: Tc=>3Tc, "semi"-pert. > 3Tc.

'81=>'89: coarse lattices, far from continuum limit: strongly first order.

>'89: deconfining transition *weakly* first order (APE, Columbia).

(Some) correlation lengths *grow* by ~ 10 near T_d!

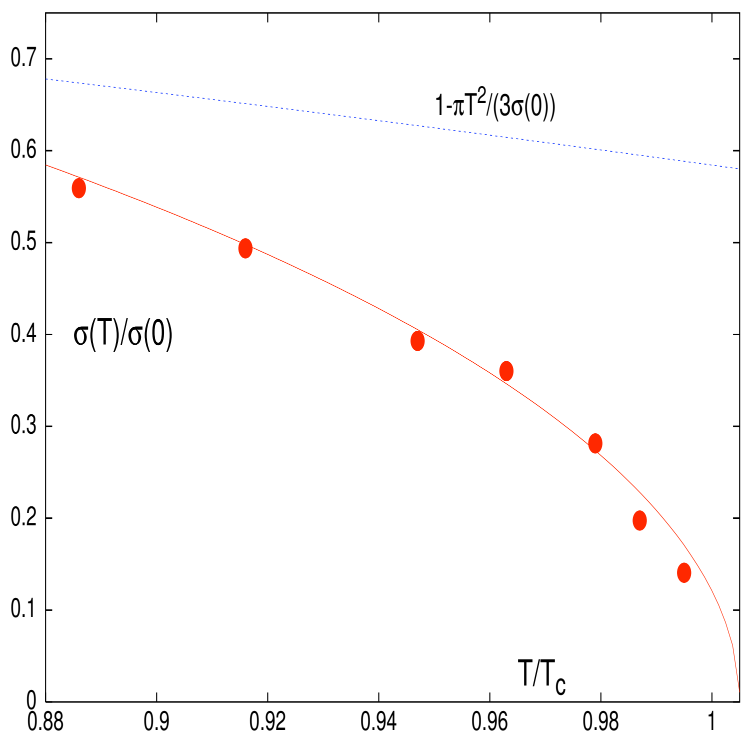
SU(3) “Pure” Gauge: *Weakly* First Order

Latent heat: Δe / e_ideal ~ 1/3 (vs 4/3 in bag model). So?
Look at physical correlation lengths, related to two point function of loops

T<Tc

string tension

$$\frac{\sigma(T)}{\sigma(0)}$$



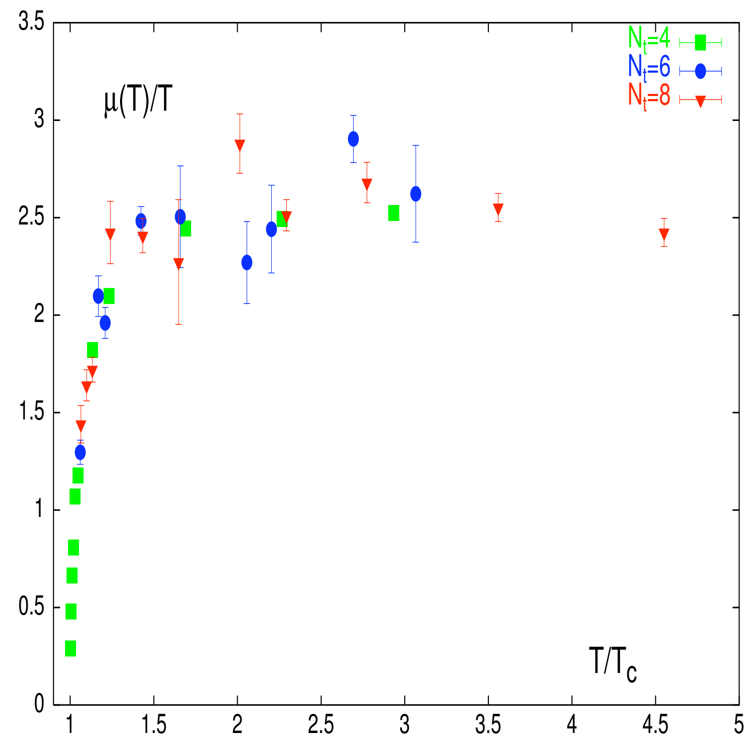
.9 Tc Tc

FIG. 1:

T>Tc

Debye mass

$$\frac{m_{Debye}(T)}{m_{Debye}(0)}$$



Tc 3 Tc

FIG. 1:

Bielefeld

(Some) physical correlation lengths grow by ~ 10!

$$\frac{\sigma(T_d^-)}{\sigma(0)} \approx \frac{m_{Debye}(T_d^+)}{m_{Debye}(1.5T_d)} \approx \frac{1}{10}$$

Lattice: *Non*-pert. QGP: T_d => 3 T_d

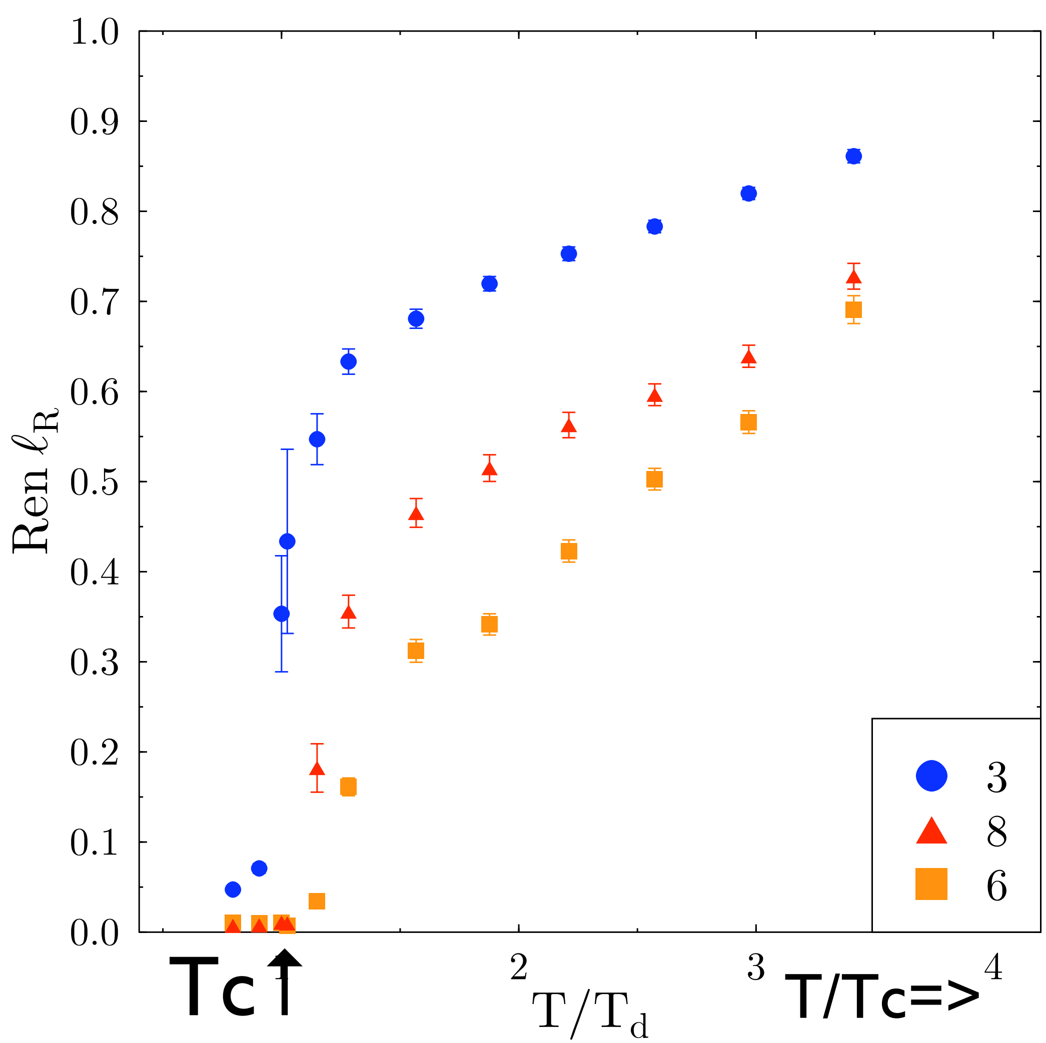
In pert. theory, ren'd (triplet) loop ~ 1 + ...

(Ren.'d) triplet loop < 1 for T_c => 3 T_c => *non-perturbative* QGP ≤ 3 T_c

Also: persistence of bound states...

(ren.'d, triplet) Polyakov loop ↑

$\langle \ell_{ren} \rangle$ ↑



<=1.0

Tc↑ T/Tc=>

3 = test quark

8 = test meson (qk +anti-qk)

6 = test di-qk

Dumitru, Hatta, Lenaghan, Orginos, & RDP. Also: Bielefeld.

Lattice Thermo: *Big* changes *with* Quarks

QCD:"2+1" flavors (up & down light, strange heavy):

$T \rightarrow \infty$: ideal gas limit increases by ~ 3.

pure glue: 16 times pressure for massless boson = $\pi^2 T^4/90$

3 massless flavors: 48.5 times pressure for 1 boson =...

Still: pressure rapidly approaches ideal gas by ~3 times Tc

T_c: *decreases* by ~ 2. Assured: Tc decreases as # flavors increases.

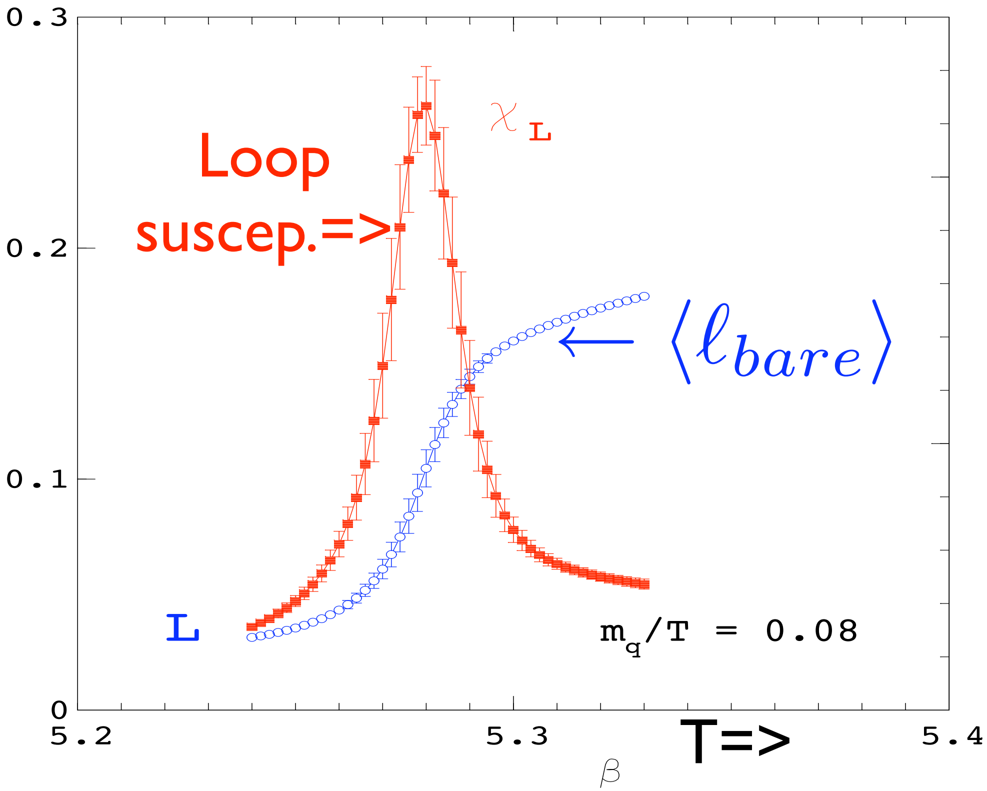
QCD: Tc ~ 175 ± ? MeV

Not close to continuum limit; hard getting quarks light enough (state of art: kaons ok, pions not)

T < Tc: in "confined" phase with pions (chiral symmetry broken), pressure *small:* turns on only *near* Tc.

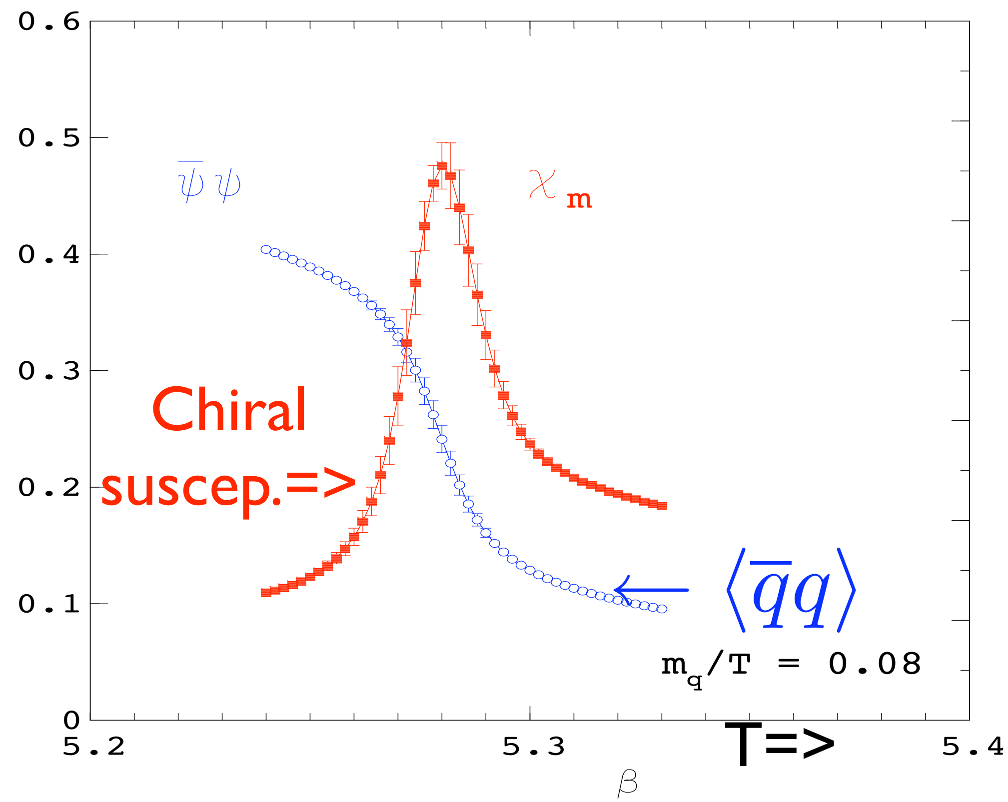
Lattice: *Always ONE* Phase Transition!

Could be *two* transitions, deconfining and chiral. NEVER seen for any quark mass.



<= (bare) Polyakov loop vs lattice coupling ~ temperature. Also: loop susceptibility.

=> chiral order parameter vs lattice coupling ~ temperature. Also: chiral susceptibility.

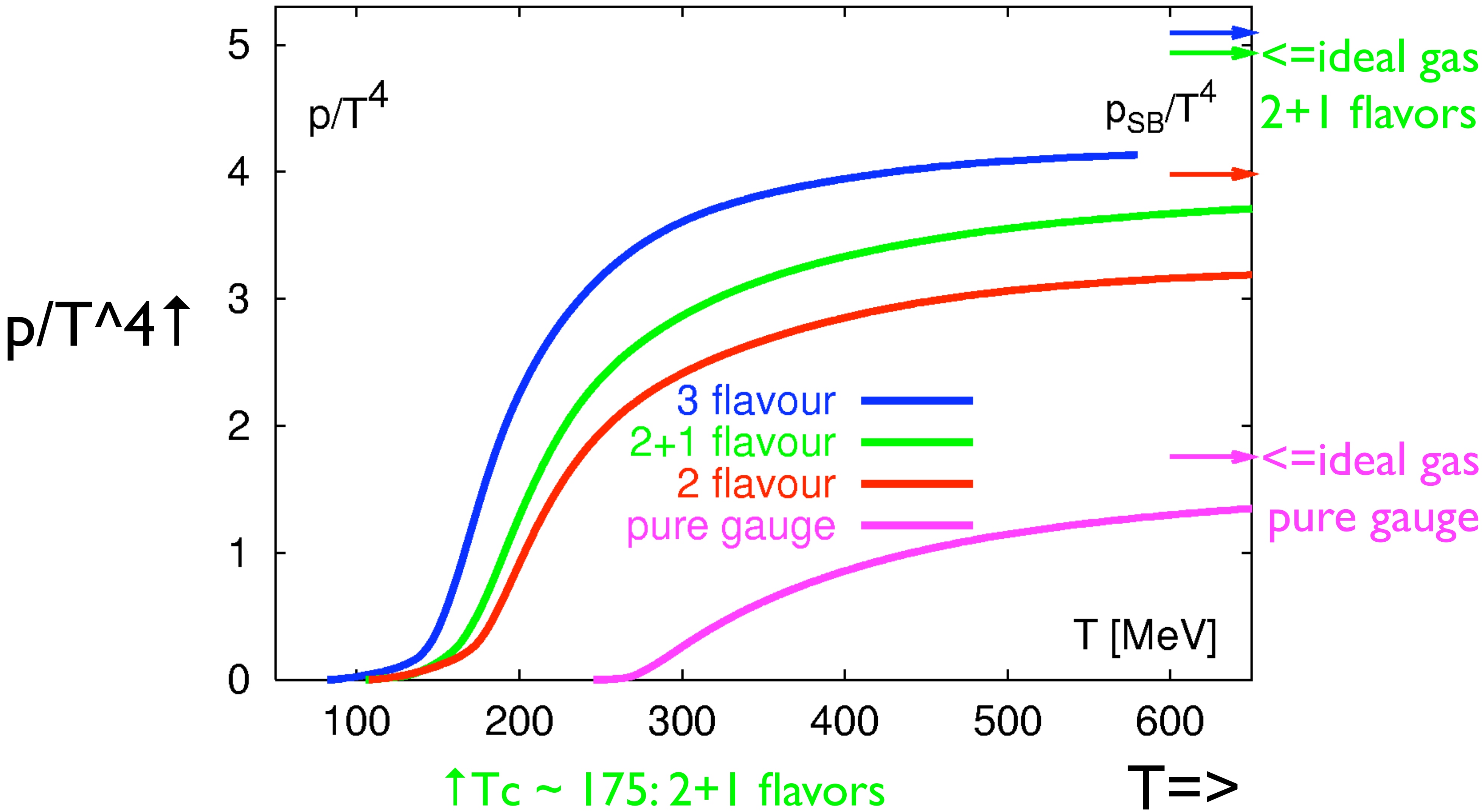


Both susceptibilities peak at SAME temeprature!

Lattice: Pressure vs T, Different # Flavors

QCD: "2+1" flavors (up & down light, strange heavy): BIG changes

p=p(T)=pressure. Plot p/T^4, => constant as T $\rightarrow \infty$ (asymp. freedom)



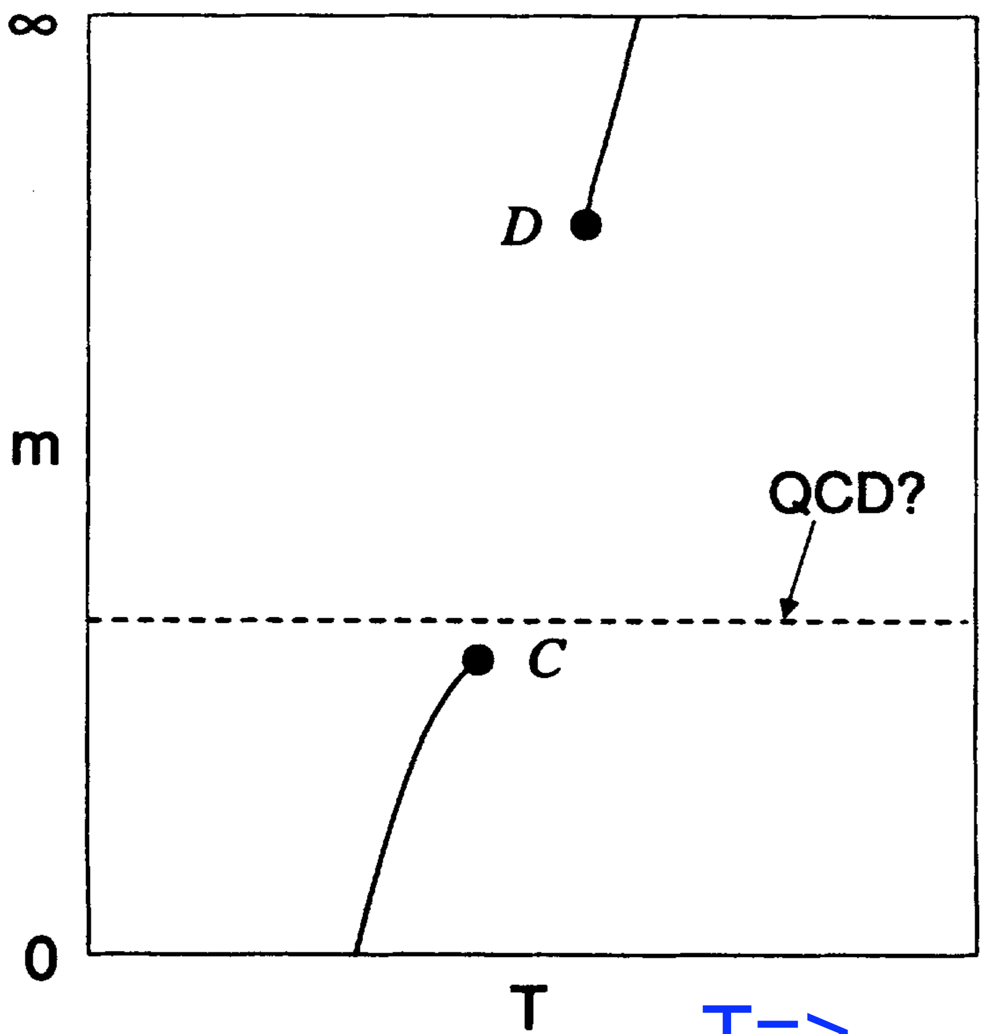
↑Tc ~ 175: 2+1 flavors

↑Tc ~ 270: pure gauge

Lattice: Order *VERY* Sensitive to Quarks

"Columbia" phase diagram: keep up, down, strange quarks in fixed ratio, vary overall mass scale = m.

m ↑



T=>

First order for:

pure gauge (m = ∞)
3 massless flavors.

But deconfining (D) and chiral (C) critical end-points!

Today:

QCD ~ *crossover*

=>*No* phase transition.

True today. Role of axial U(1)?

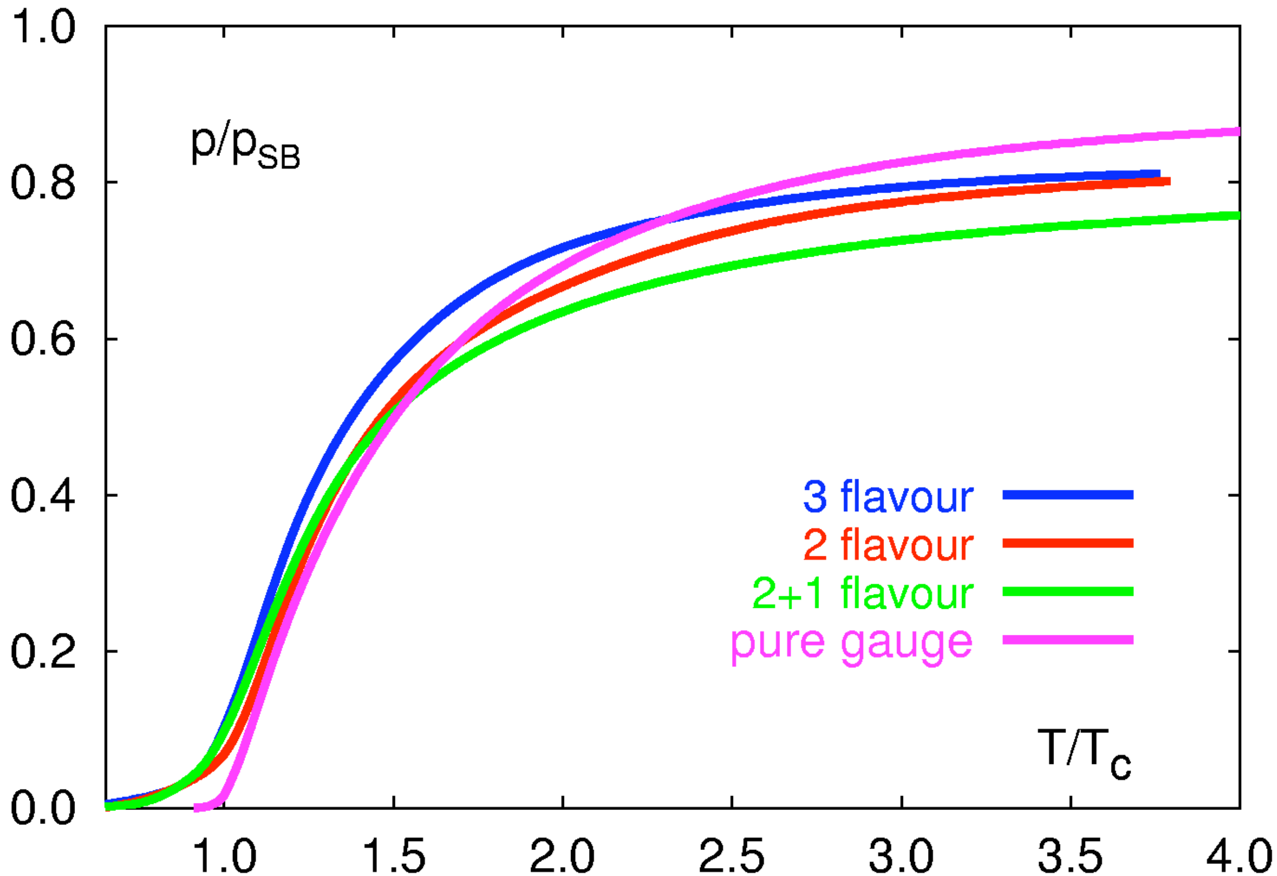
Lattice: "Flavor Independence"

Lattice finds *amazing* property:
properly scaled, pressure *with* quarks
like that *without*: *Bielefeld.*

$$\frac{p}{p_{ideal}}\left(\frac{T}{T_c}\right) \approx universal$$

1.0=>

pressure/
ideal gas↑



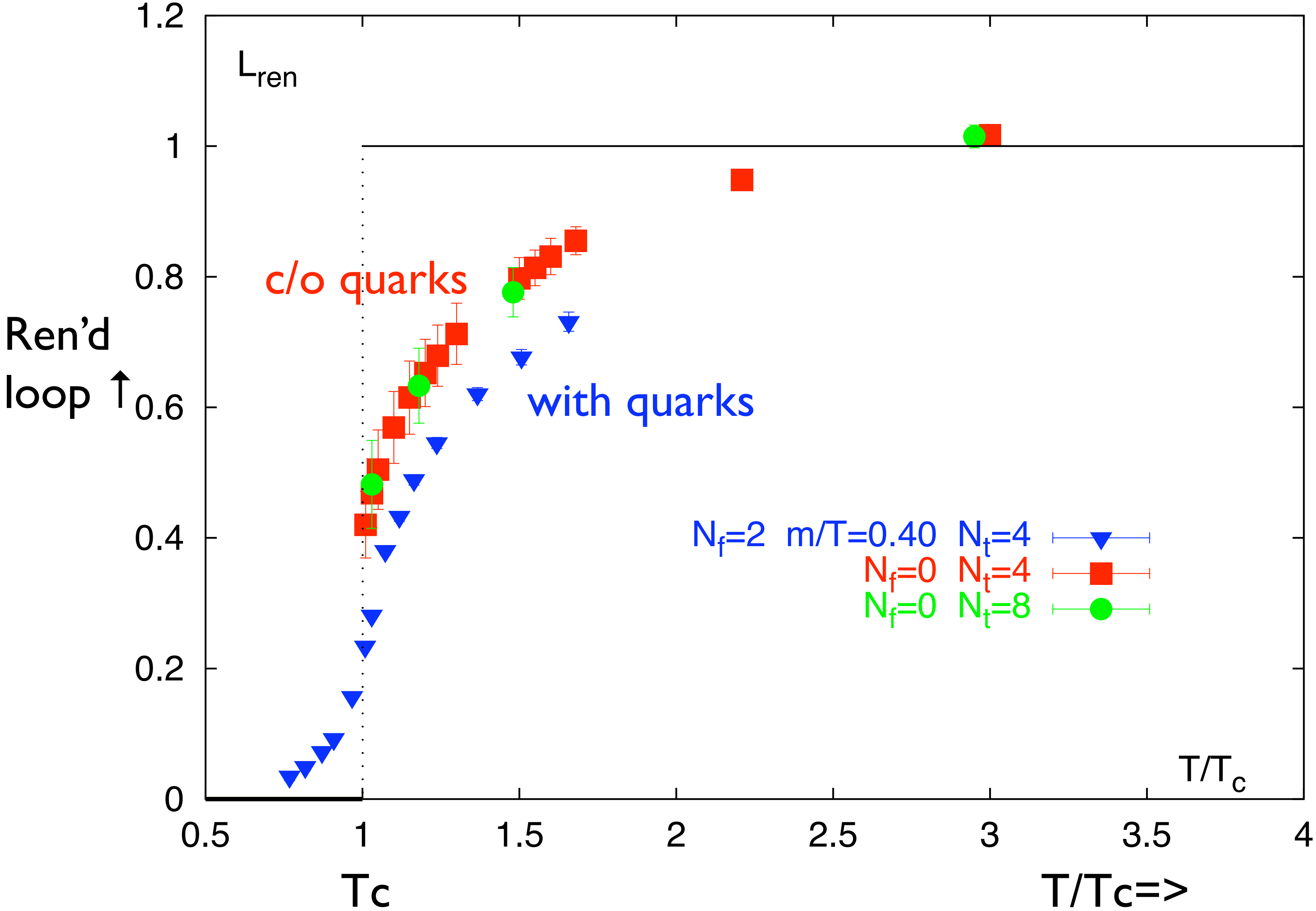
=> pressure *dominated* by *gluons?*

T/Tc=>

(Ren.'d) Polyakov Loop *with* Quarks ~ Pure Gauge

(Ren.'d) Loop approx.'y same with quarks as without =>

pressure dominated by gluons? (= Polyakov loop)



Bielefeld: lat/0312015

Two flavors, kaon masses

Hunting for the "Unicorn": the Quark-Gluon Plasma, in Heavy Ion Collisions

"Unicorn" & the QGP: Scott, Stock, Gyulassy...

Why do AA? *Big* Transverse Size.

First, some essential definitions. One can collide:

pp: protons on protons. Serves as benchmark for "ordinary" hadronic coll.'s.

AA: nucleus with atomic number A on the same type of nucleus.

pA: proton on a nucleus. At RHIC, often dA (d = n+p ~ p) for accelerator reasons (charge/mass ratio) Serves as test to tell pp from AA.

WHY AA? Nucleon's are like hard spheres, so nuclear size $r_A \sim A^{1/3}$

Biggest: Pb (lead) or Au (gold), A ~ 200 => r_A ~ 7.

Transverse radius of nucleus $\sim A^{2/3}$ => trans. size ~ 50 x proton.

A $\rightarrow \infty$: *infinite* nuclear matter. A~200 close to ∞? Decide by *experiment.*

(Very) roughly: transition from p to large A for A~30-50.

Colliders: Energy, Machines

Particles accelerated in rings. Highest energy is for two rings, with particles travelling in opposite directions = *collider.*

Basic invariant: total energy in the center of mass, $E_{c.m.} \equiv \sqrt{s}$

For AA collisions, energy *per* nucleon is $\sqrt{s}/A \equiv \sqrt{s_{NN}}$

Machines:

	$\sqrt{s}/A$	
SPS @ CERN:	5 => 17 GeV	(fixed target)
RHIC @ BNL:	20, 130, 200 GeV	(collider)
LHC @ CERN:	5500 GeV = 5.5 TeV	(collider, > 2007)

SPS = Super Proton Synchotron: CERN @ Geneva, Switzerland.
RHIC = Relativistic Heavy Ion Collider; BNL @ Long Island, NY
LHC = Large Hadron Collider.

Collider Kinematics

At low energies, form one "blob" which is radially symmetric = Landau model.

At high energies (s >> 1 GeV) particles go through each other. Use:

Momenta transverse to the beam: p_t

Momenta along the beam = p_z Exp.'y, not useful. Instead:

Rapidity = y: $y = \log((E + p_z(/(E - p_z))$ y=0 = 90^o for collider

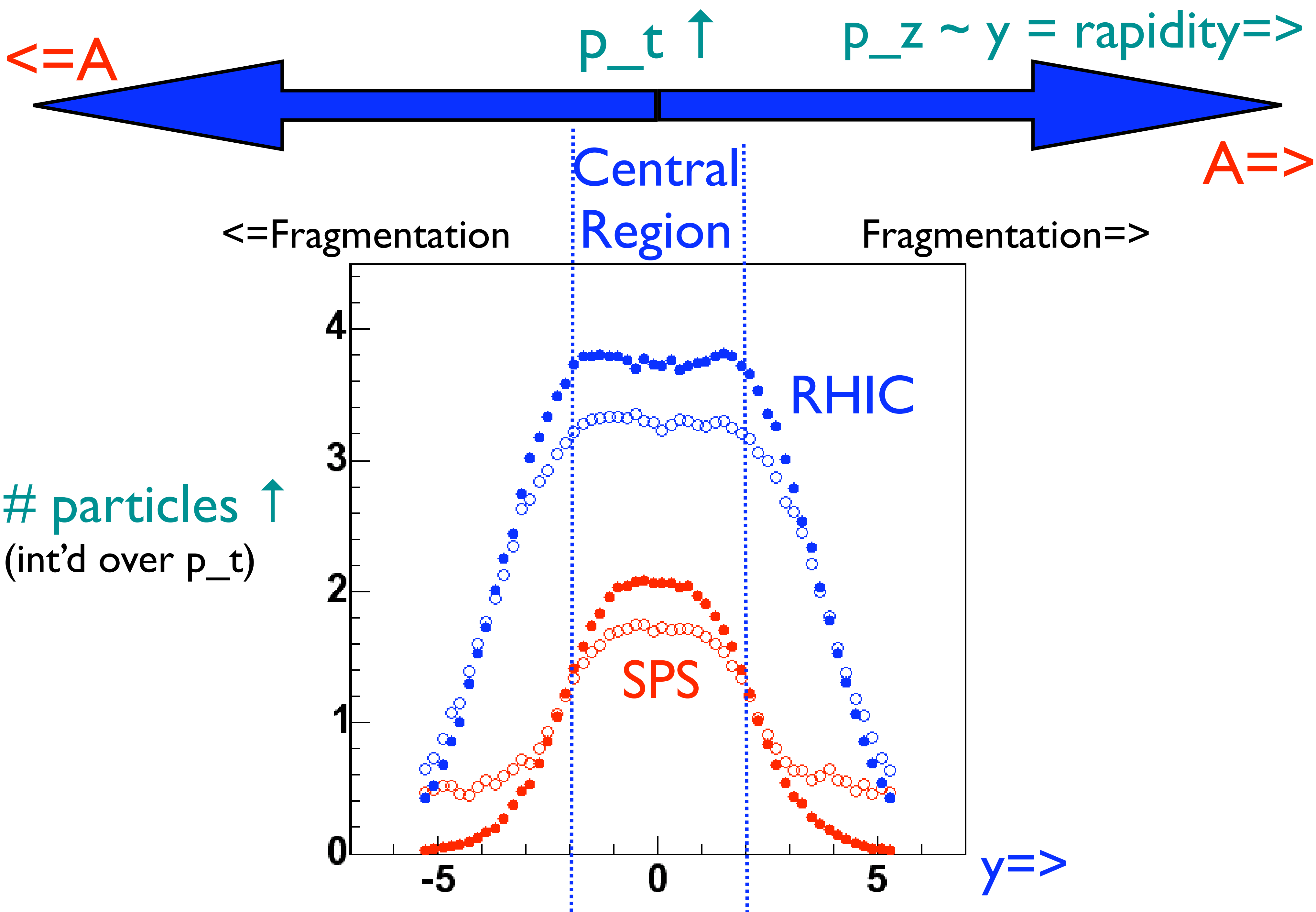
Pseudo-rapidity: η If one doesn't have particle ID, so assume $E = \sqrt{p_t^2 + p_z^2}$

Usually: # particles vs p_t, & y: *most particles at zero p_t, zero y.*

"Central regime:""free" of incident nucleons, rapidity y ~ 0
=>most likely to exhibit T ≠ 0 ≈ *small* net baryon density

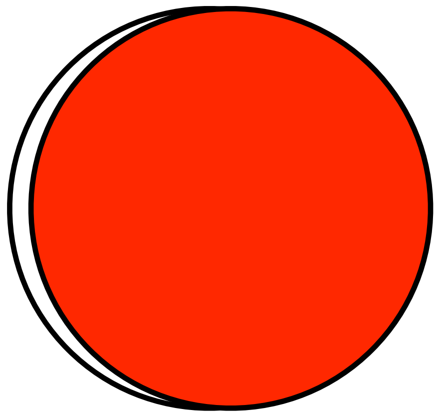
"Fragmentation regime": where incident nucleons go, rapidity ~ max.

Relativistic Kinematics @ Collider

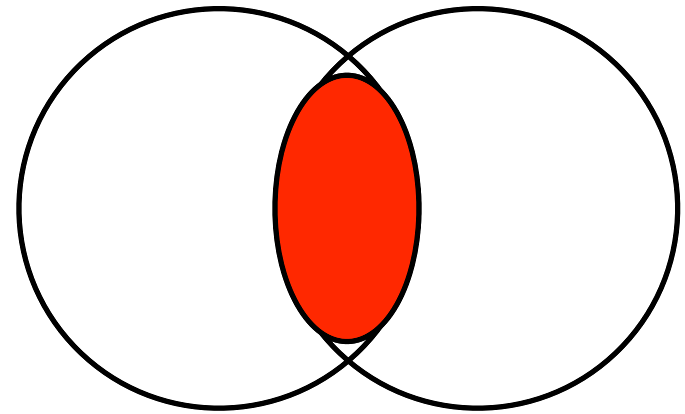


AA collisions: Central vs Peripheral

Central:
Maximum
Overlap



Peripheral=>
"Almond" of
overlap region



Theoretically: would like to compare central AA from small to large A. Takes a lot of beam time. But running with given A, *automatically* measure peripheral collisions.

Exp. variable: # participants.

= 400 in central (= 200 + 200)

= 100 => 400 in peripheral (Glauber & other models; agree to 10%)

Typical Heavy Ion Event @ RHIC

Total # particles = 1000's. Exp.'y: dealing with high event rates, data acquisition...
AA @ RHIC similar to pp collisions @ LHC.

Experiments @ RHIC:

STAR: big, 4 π coverage, y = ±2

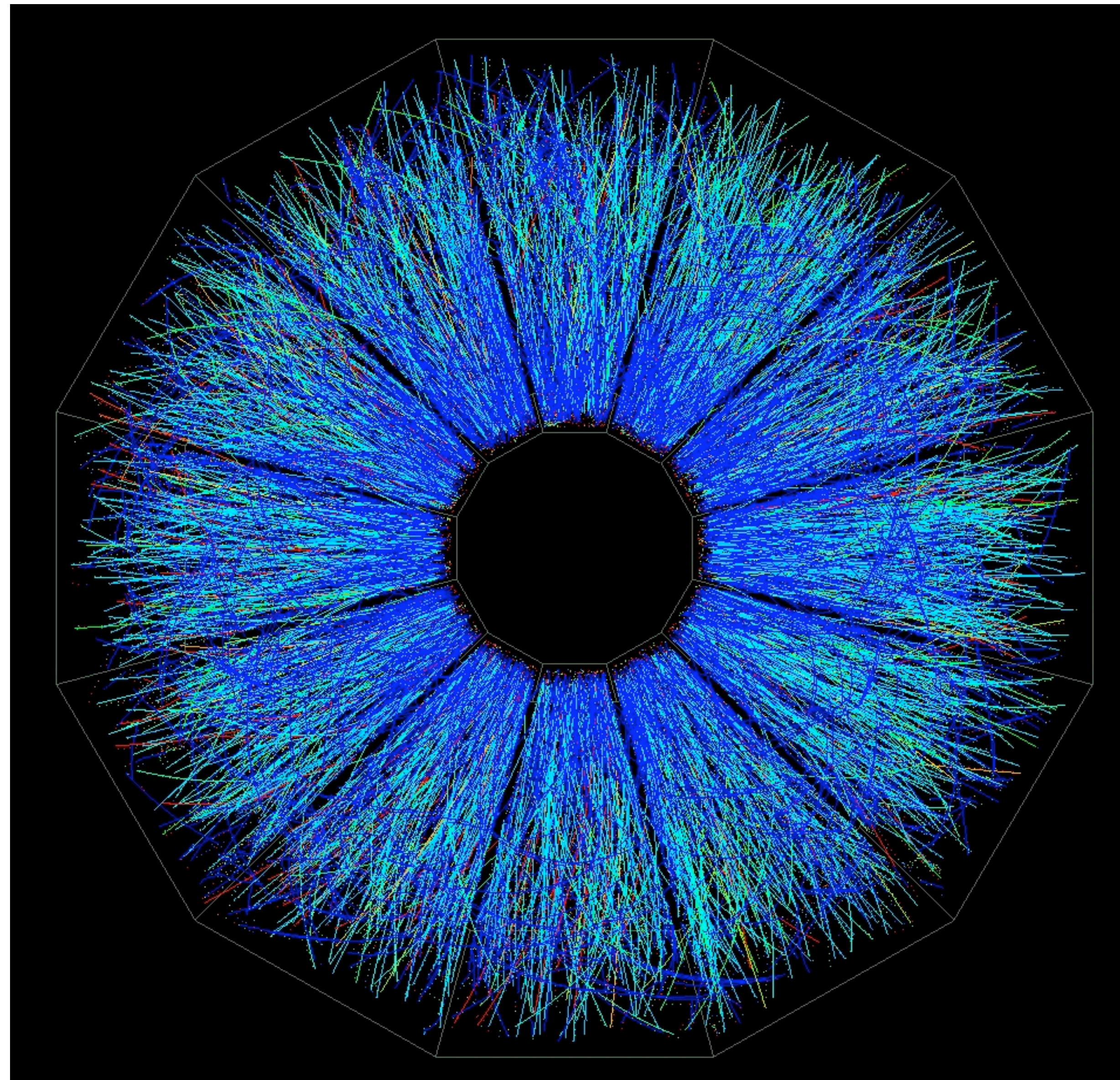
PHENIX: big, elec.-mag.,y = ±2

PHOBOS: small, all rapidity

BRAHMS: small, all rapidity

big = 400 experimentalists
(~ "participants")

small = 50 exp.'s.



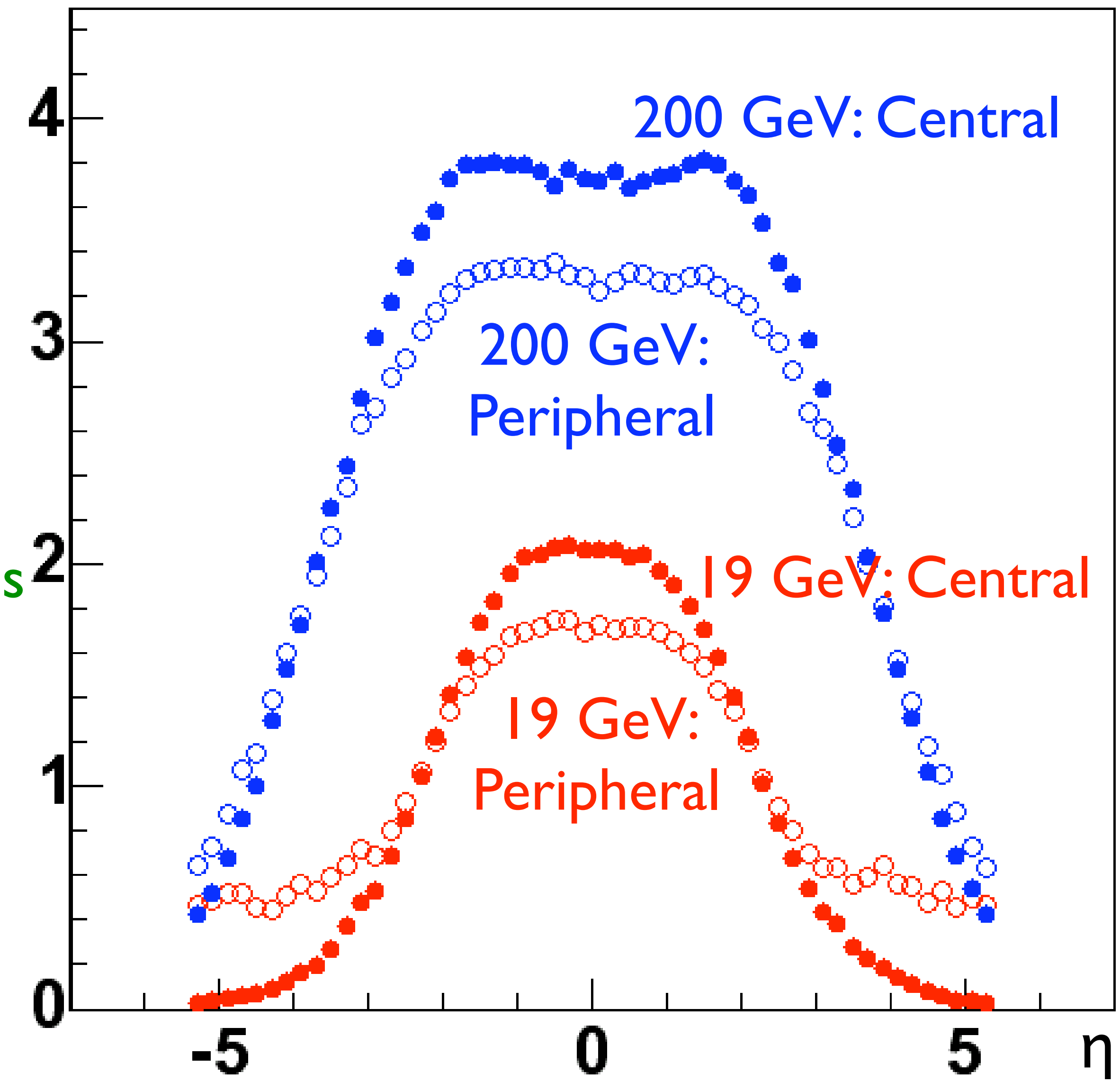
The “Body” of the Unicorn: Soft Momenta, pt < 2 GeV

Most particles are at soft momentum.
With Tc ~ 200 MeV, *expect* thermal particle distributions to p_t ~ 2 GeV.
Thousands of particles, should be able to use hydrodynamics...

Particle Distributions vs η, Energy: "Central Plateau" @ RHIC

dN/dη / ↑
participants

N = # particles



η = pseudo-rapidity

200 GeV = Highest energy @ RHIC 900 particles/unit η

19 GeV = Highest energy @ SPS 600 particles/unit η

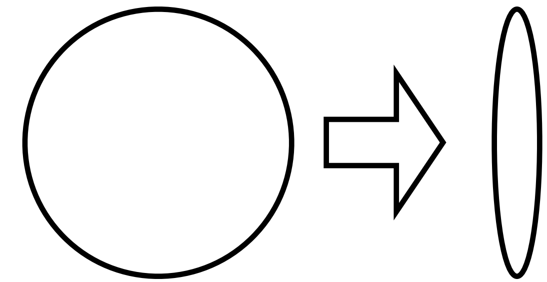
Particle dist.'s *qualitatively* same between central & peripheral.

η ~ 0 = 90^o for collider. central region: η = ± 2 @ RHIC

η ~ maximum = down the beam pipe. fragentation region: |η| > 2 @ RHIC

Why do AA? "Saturation" as a Lorentz Boost

At high energies, incident nucleus is *Lorentz contracted*.
=> color charge of incident nucleus gets "squashed".



$\leftarrow A^{1/3} \rightarrow$

McLerran & Venugopalan: color charge bigger by $A^{1/3}$

$A \rightarrow \infty$: can use *semi-classical* methods.

@ central rapidity, gluon *saturation* = Color Glass.

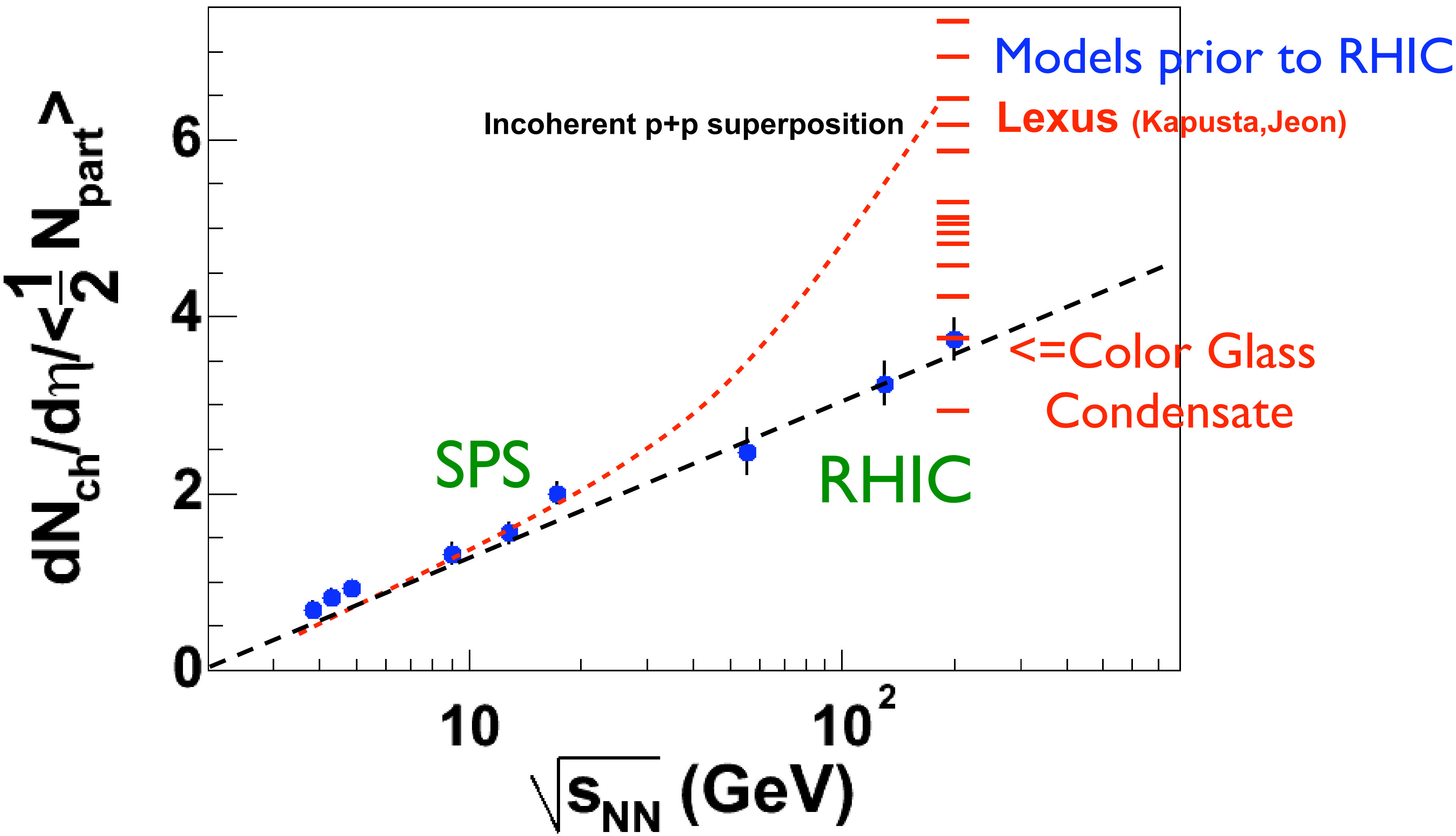
As semi-classical, predicts *logarithmic* growth in multiplicity:

$$\frac{dN}{dy} \sim \frac{1}{g^2(\sqrt{s}/A)} \sim \log(\sqrt{s}/A)$$

First surprise from Day 1: NO big increase in multiplicity. Approx. log growth.

Also: expect avg. momentum to grow similarly $\langle p_t \rangle \sim \log(\sqrt{s}/A)$
(Krasnitz & Venugopalan)

Slow Growth in Multiplicity with Energy

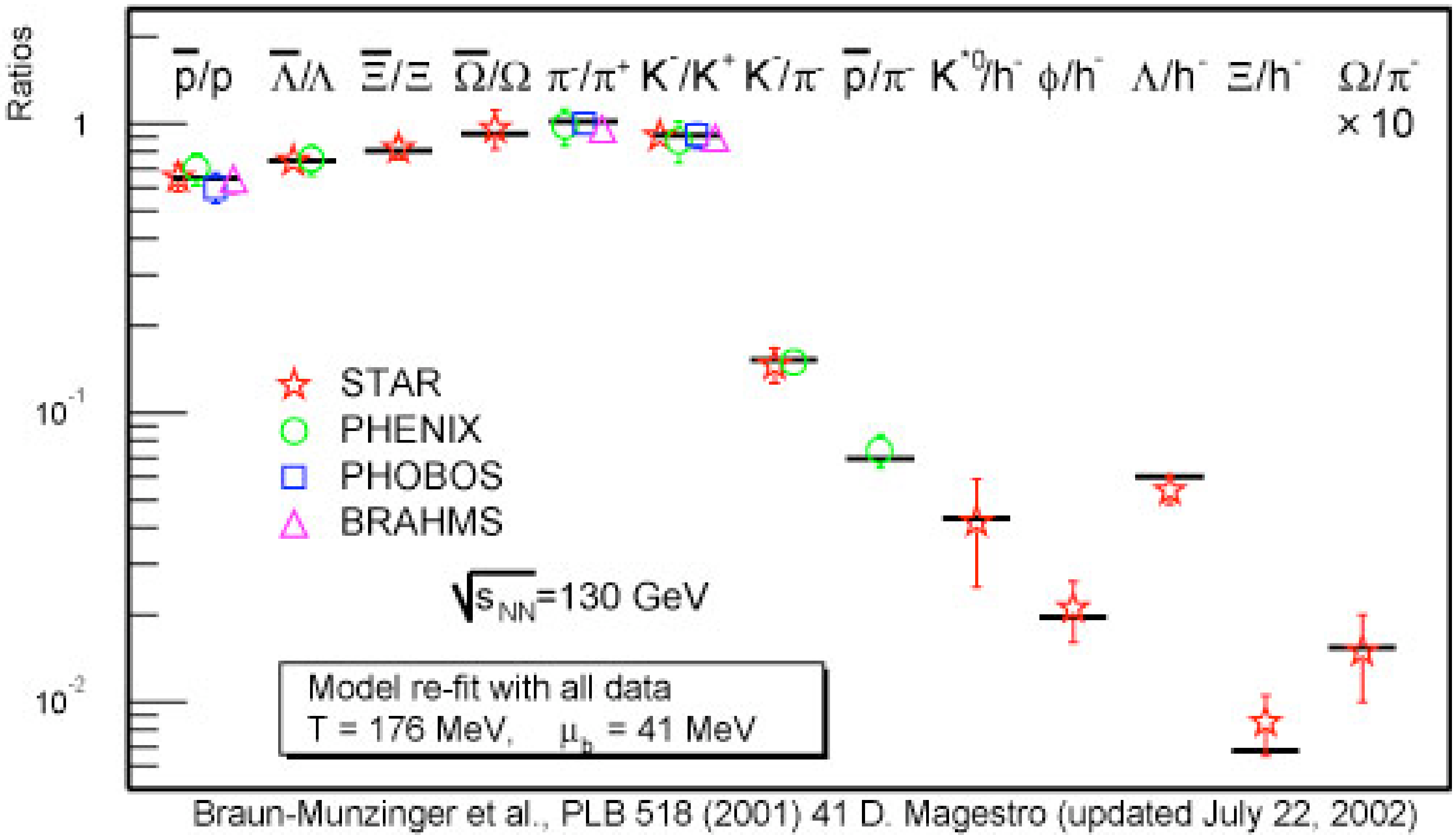


Good fits to overall multiplicity, centrality dependence (Kharzeev, Levin, Nardi)

But: STAR: from 130 => 200 GeV, multiplicity increases by 14%,
but NO change in $\langle p_t \rangle$ ± 2%. Vs. > 7% increase from Color Glass!

Total Chemical Ratios *Appear* in Thermal Equilibrium

$$T_{ch} = 175\ MeV$$



OVERALL chemical abundances *well* fit with T_ch = 175 MeV, μ_baryon ~ 0
(Becattini, Braun-Munziger, Letessier, Rafelski, Redlich, Stachel, Tounsi...)

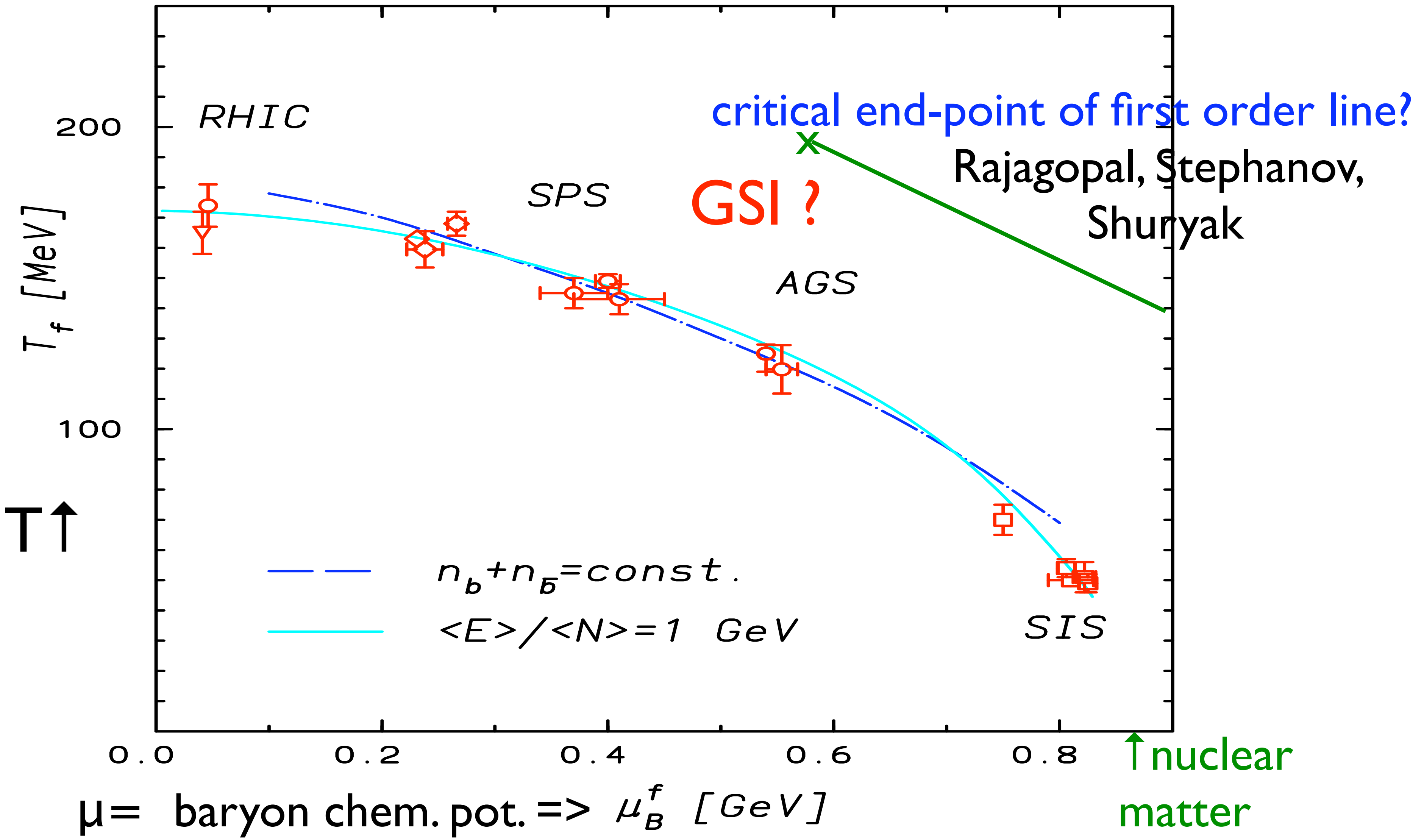
N.B.: even for multi-strange baryons, with relative abundances ~.1% of pions.

Chemical Ratios vs Energy in AA: T-μ plane

Similar fits for chemical abundances also work at lower energies. Baryons still present at y=0, so need to add baryon chemical potential, μ.

Find *line* in T-μ plane. Similar fits work for pA, pp - *everywhere!*

(With corr.'s for finite vol., canonical ensemble...) => *NOT* conclusive.

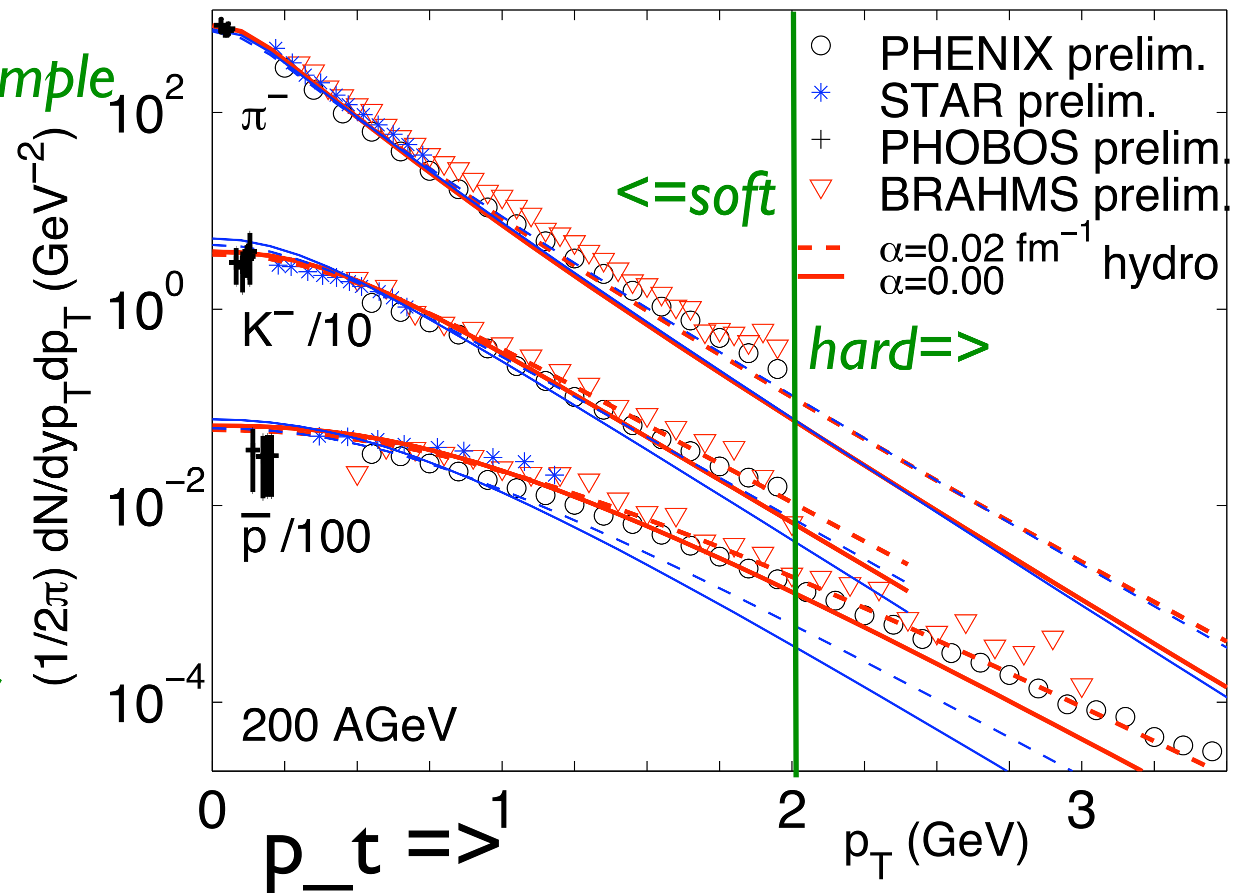


p_t Spectra *Appear* In Thermal Equi. ~ *Hydrodyamics*

$T_{kin} \approx 100 MeV (\ll T_{ch}!)$ *Local* Boost Velocity $\beta \sim .7c$

Hydro. gives good description for most particles, at low p_t< 1GeV.

Assumes initial conditions: starts above Tc in thermal equilibrium, *simple* Equation of State (1st order!)
Ideal hydro.: NO viscosity...



Large local boost velocity β~ .7 c.
Spectra of heavy particles "turn over" at low p_t. β=β(radius).

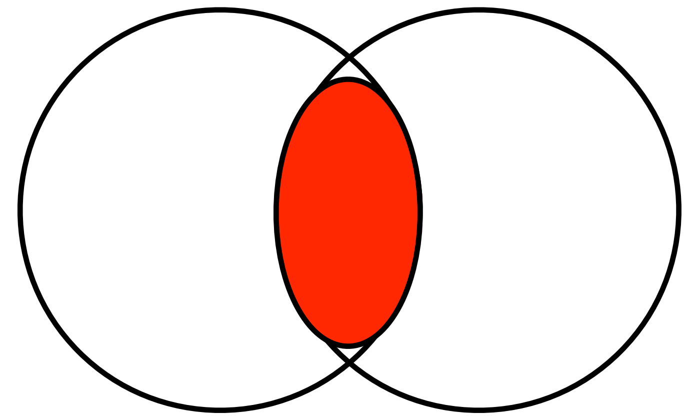
RHIC: first clear evidence for boost velocity: big!
Direct fits similar: "Blast-wave"

Hydro *needs* to assume applicable from *very* early times, .6 fm/c!

Heinz, Hirano, Kolb, Rapp, Shuryak, Teaney... (above Heinz & Kolb)

Success of Hydro.: v2 = Elliptical Flow

Peripheral Coll.'s: Start with system which is anisotropic in momentum space. Exp.'y, compute how *spatial* anistropy => *momentum* anistropy. (Ollitrault, Borghini)



$\uparrow y$

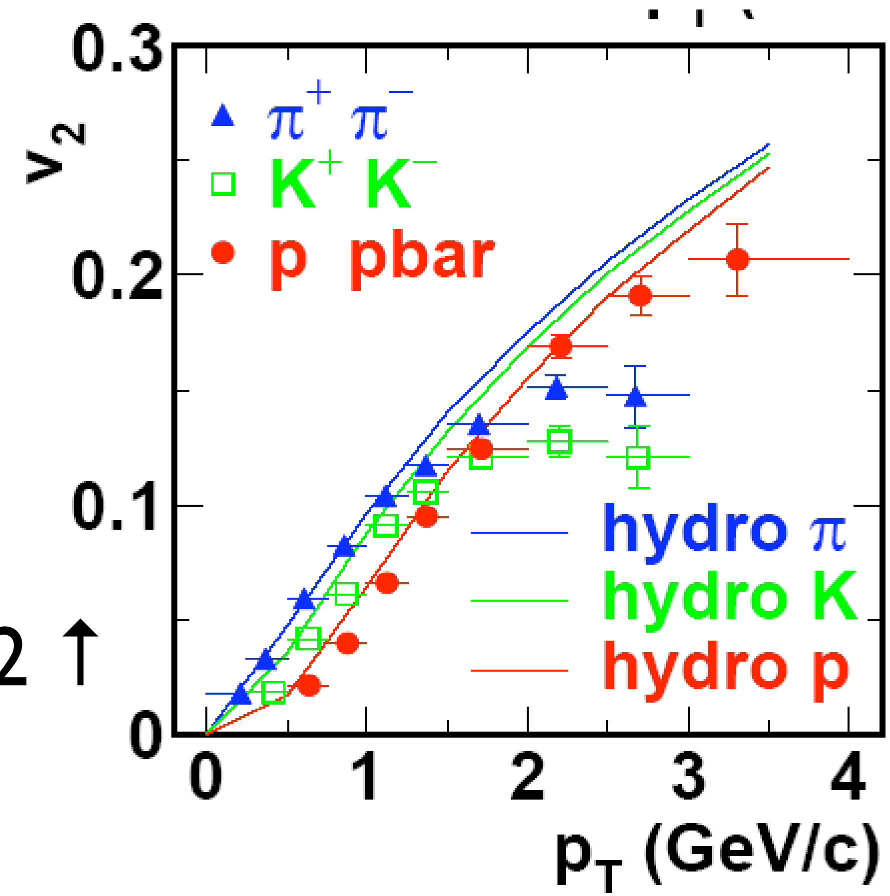
$\rightarrow x$

$$v_2 = \langle cos(2\phi) \rangle \ , \ \tan\phi = p_y/p_x$$

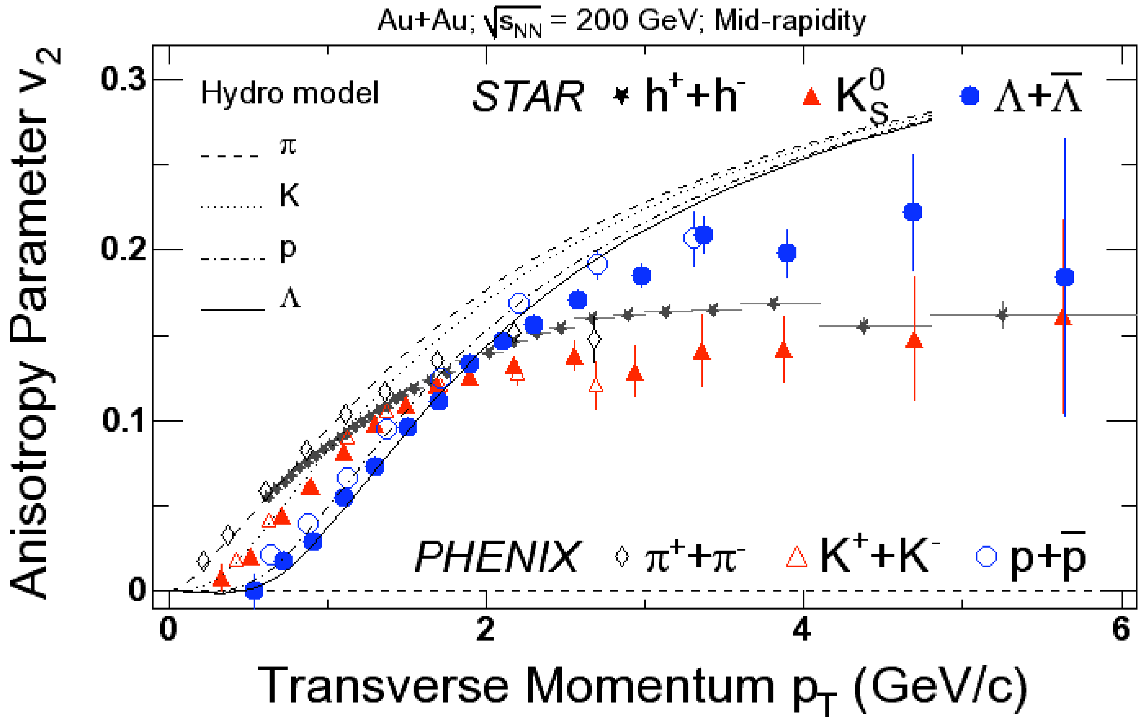
v2 => collective behavior: there is "stuff", and it sticks.

Hydro works for v2 @ RHIC, not SPS.

v_2 ↑

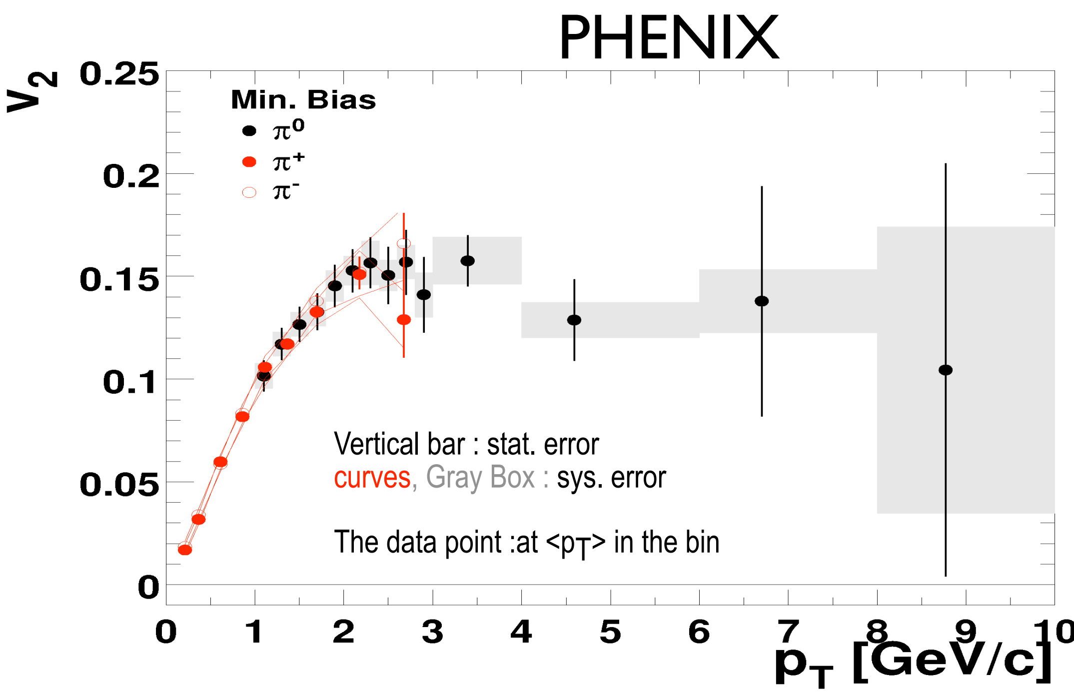


At Low p_t < 1 GeV, Hydro. works for *All* Particles



<= Hydro works for v_2
to p_t ~ 1 GeV for
π's, K's, p's, Λ's…. *everything.*

For *all* particles, v_2 *flat* for
p_t > 1 GeV => 10 GeV - ?!



Is v_2 at p_t>1 GeV measuring
collective flow, or jet-jet correlations?
Apparently: true collective flow.

So why flat?

HBT Radii: Hydro *Fails*. *"Blast Wave"* Works

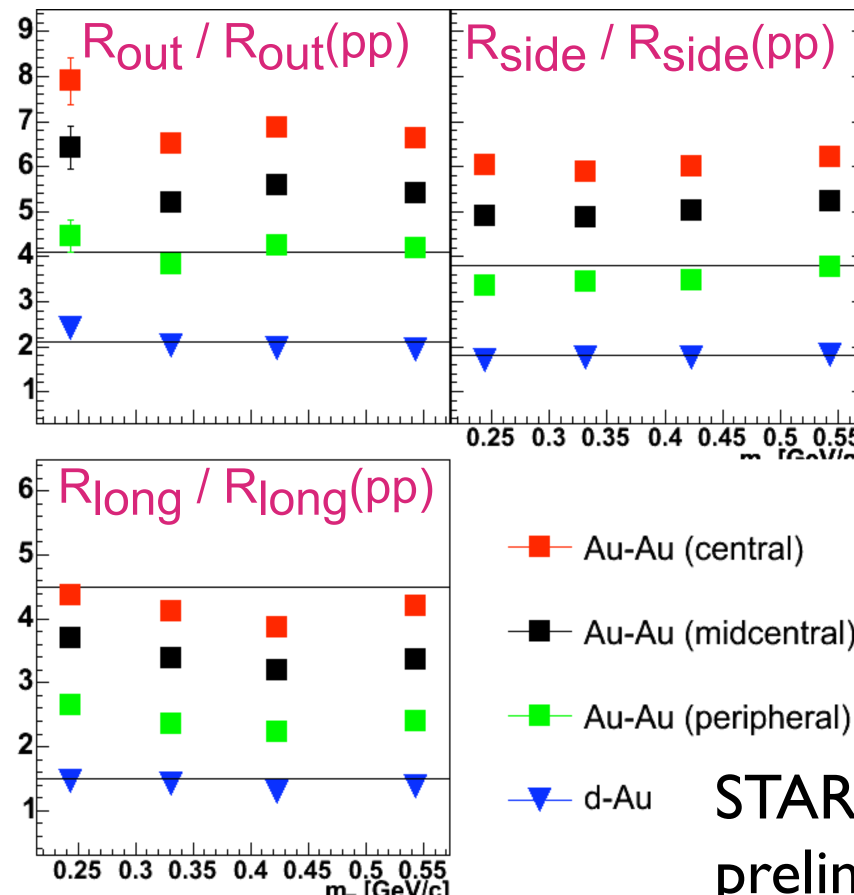
Hanbury-Brown-Twiss (HBT) radii: two-particle correlations for identical particles, used to determine size (as for stars). Typically: fall off like Gaussian.

Here: *three* directions for momentum of pion pair (Bertsch & Pratt).
HBT then gives three sizes: along beam (R_longitudinal), along line of sight (R_out), & perpendicular to light of sight (R_side).

Hydro: R_out/R_side > 1, *increases* with p_t.
Exp.: R_out/R_side ~ 1, *decreases* with p_t!

"Blast Wave" works: expanding shell.
Is a *fit*, not underlying space-time picture.

HBT radii ~ *same* in pp, dA, and AA!
Even p_t dependence same!



STAR prelim.

Body of the "Unicorn":

Majority of particles, at small momenta < 2 GeV, look superficially like thermal bath. But in detail, surprises:

HBT radii =>
space-time picture *not* yet understood.

Tail of the "Unicorn":

Look at particles at *HIGH* momentum, p_t > 2 GeV, to probe the body.

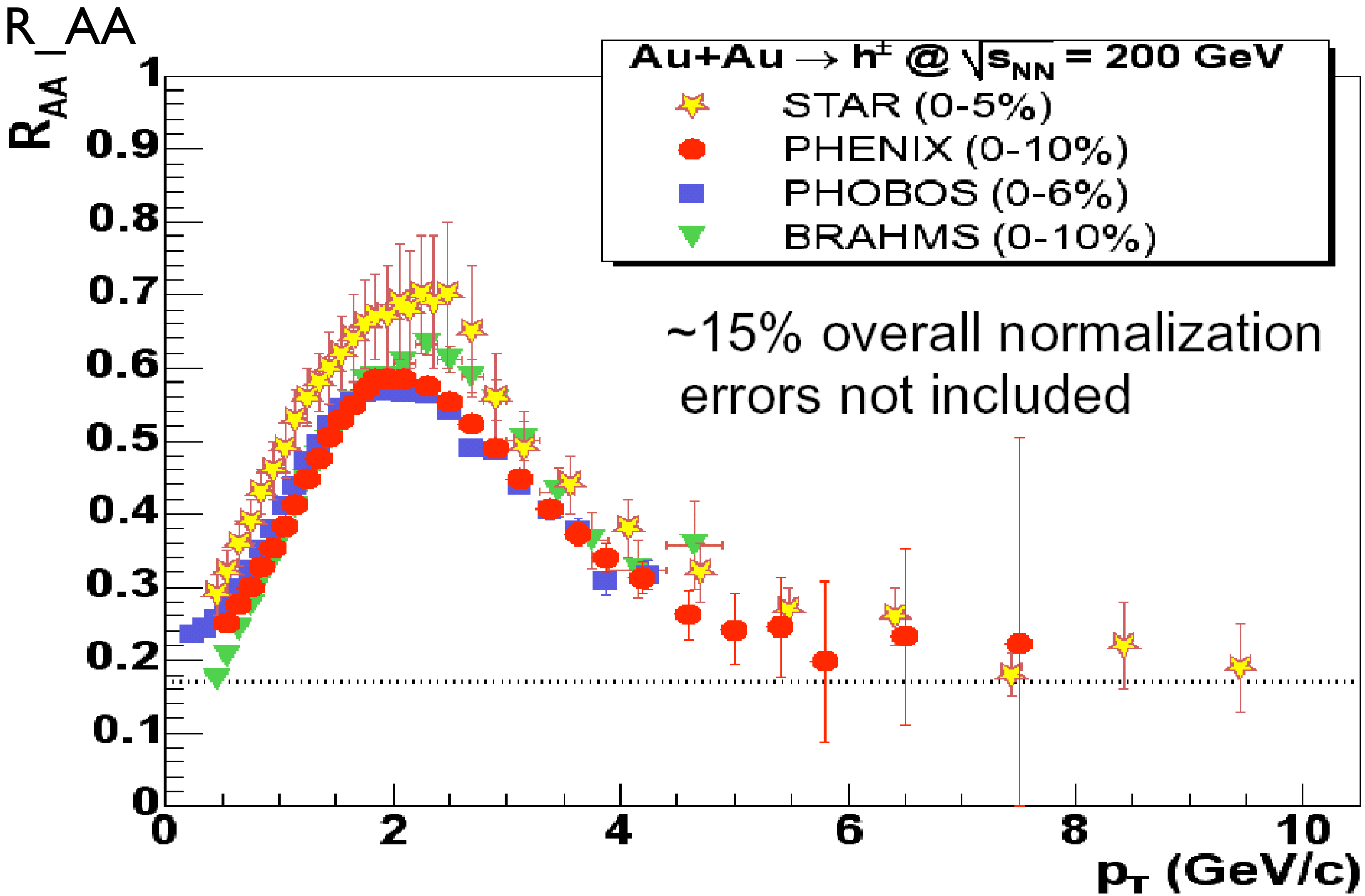
The Tail wags the (Dog) Unicorn

Clear Experimental Signal of "Stuff": R_AA

Compare spectra in AA to that in pp, especially for "hard" pt > 2 GeV:

From Day 1, "hard" spectra appear *steeper* in AA than pp => *fewer* particles.

R_AA = # particles at a *given* p_t, in central AA collision/ # particles at the *same* p_t in pp, *central rapidity*.



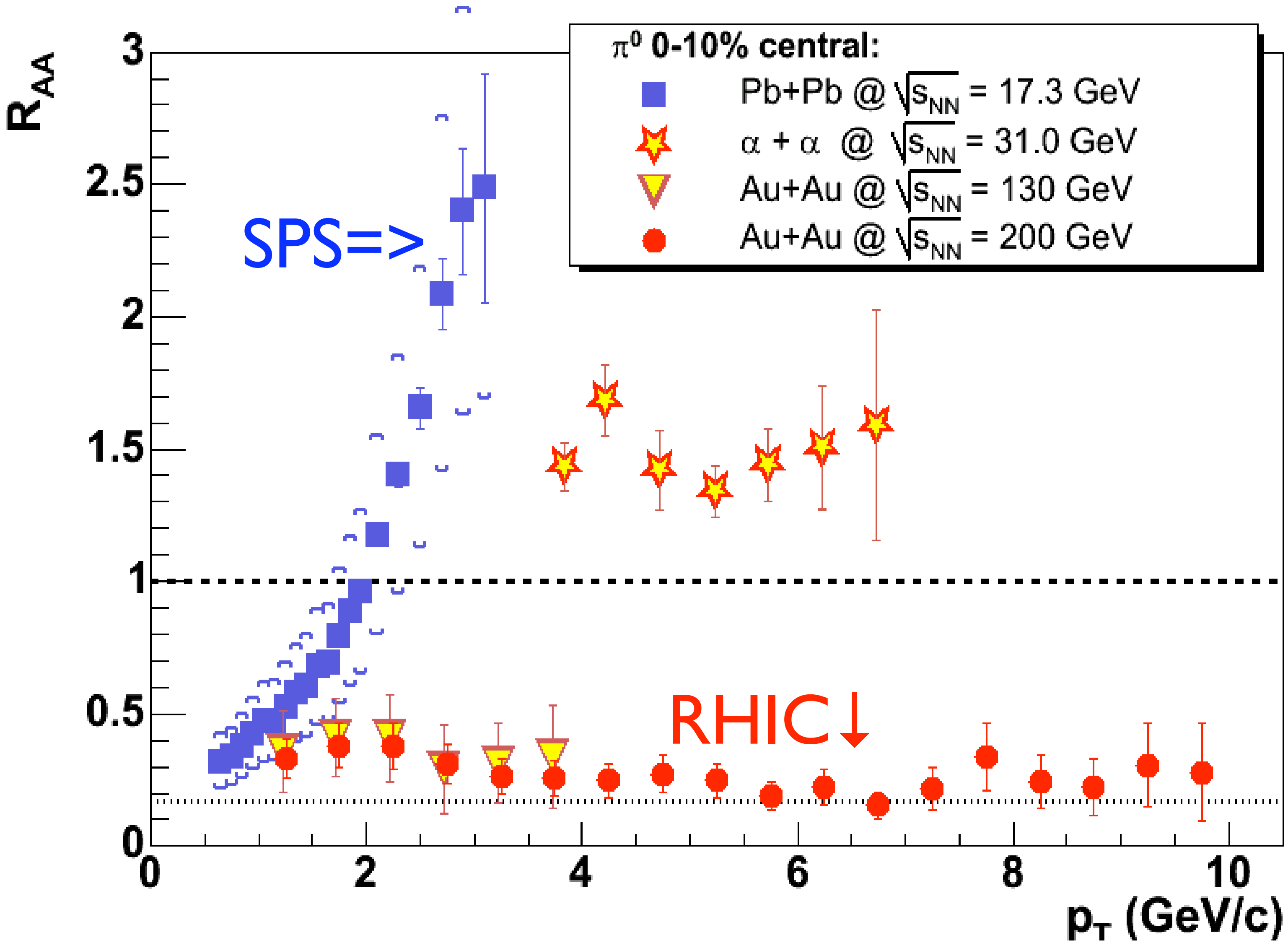
R_AA => *suppression* of hard particles in AA, vs pp.

For p_t> 6 GeV *all* particles suppressed.

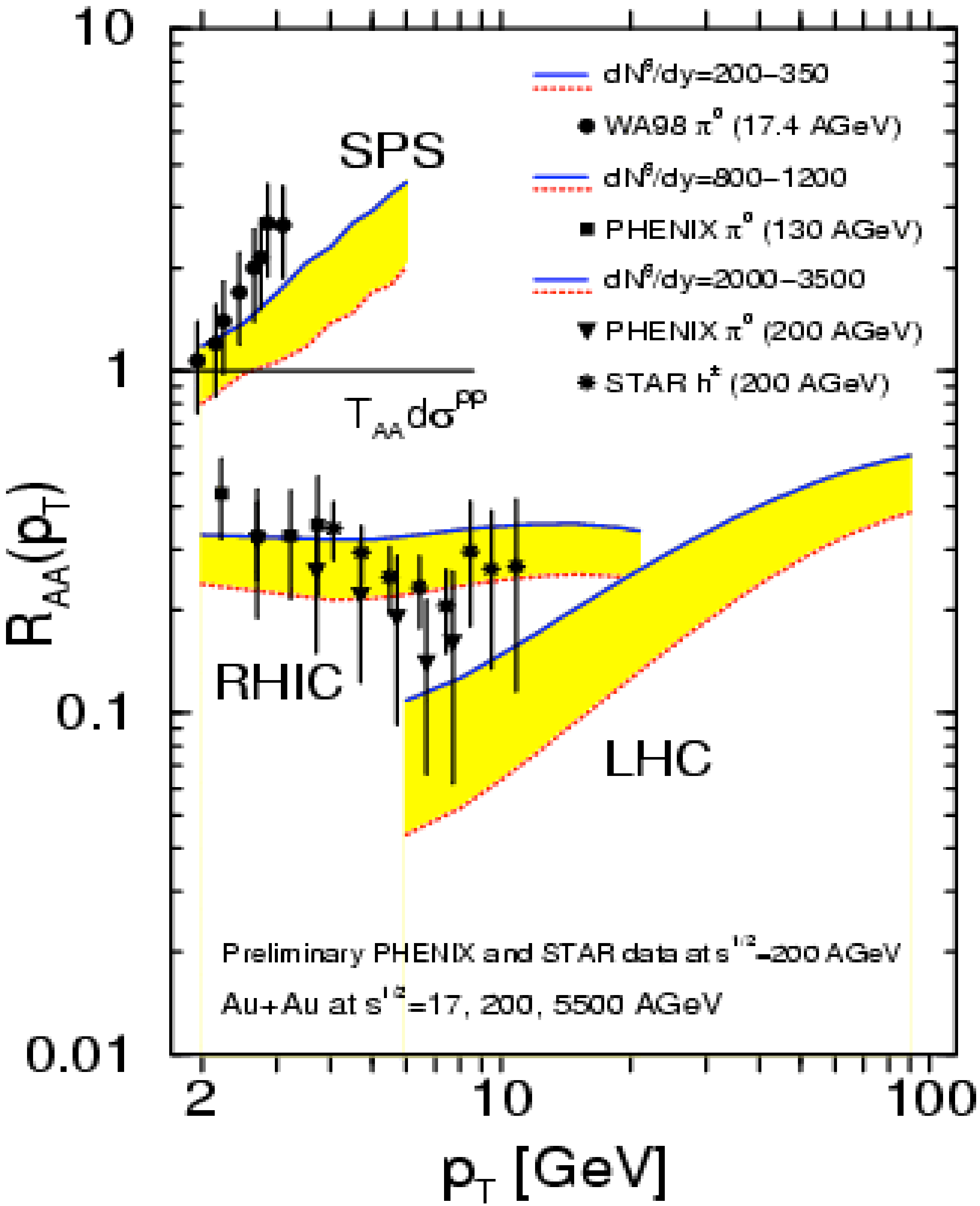
R_AA: *Enchancement* @ SPS, *Suppression* @ RHIC

Effect most dramatic for π^0's. SPS: R_AA ~ 2.5 @ 3 GeV. "Cronin"
RHIC: R_AA ~ 0.2 @ 3 GeV.

RHIC: Supp. from *energy loss* - *"stuff"* slows fast particles down.



R_AA: Qualitative Agreement with "Energy Loss"



Energy Loss: A fast particle going through a thermal bath loses energy:
Gyulassy, X.N. Wang, Vitev...Baier, Dokshitzer, Mueller, Schiff, Zakharov

<= Gyulassy & Vitev: *conspiracy* to give *flat* R_AA @ RHIC.

Need to add several effects, "Cronin", energy loss, shadowing...

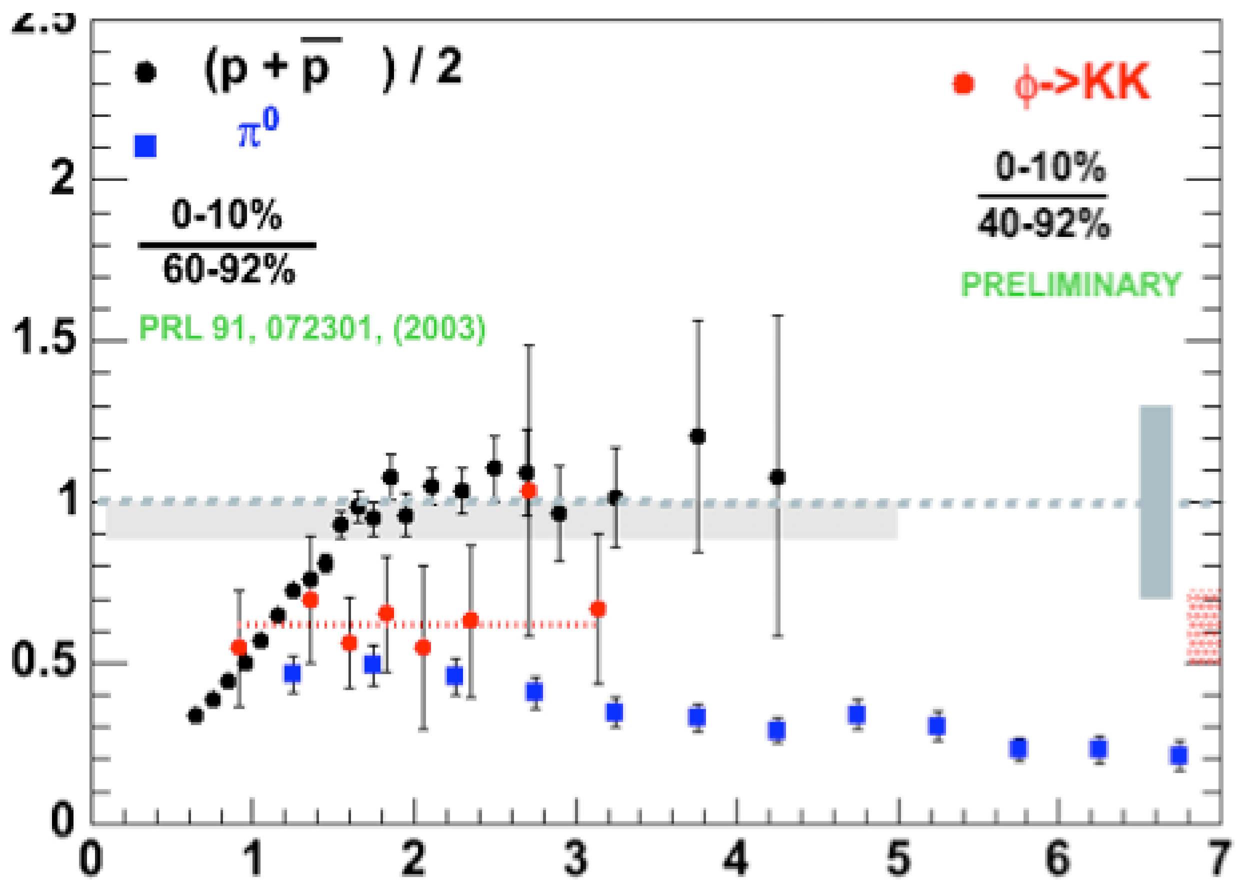
Is "flat" R_AA for π^0's special to RHIC? Will be interesting @ LHC!

Central AA: at inter. p_t, *only* mesons suppressed

R_CP: ratio for # particles at given p_t, for central to peripheral collisions
Behaves like R_AA, easier to get data.

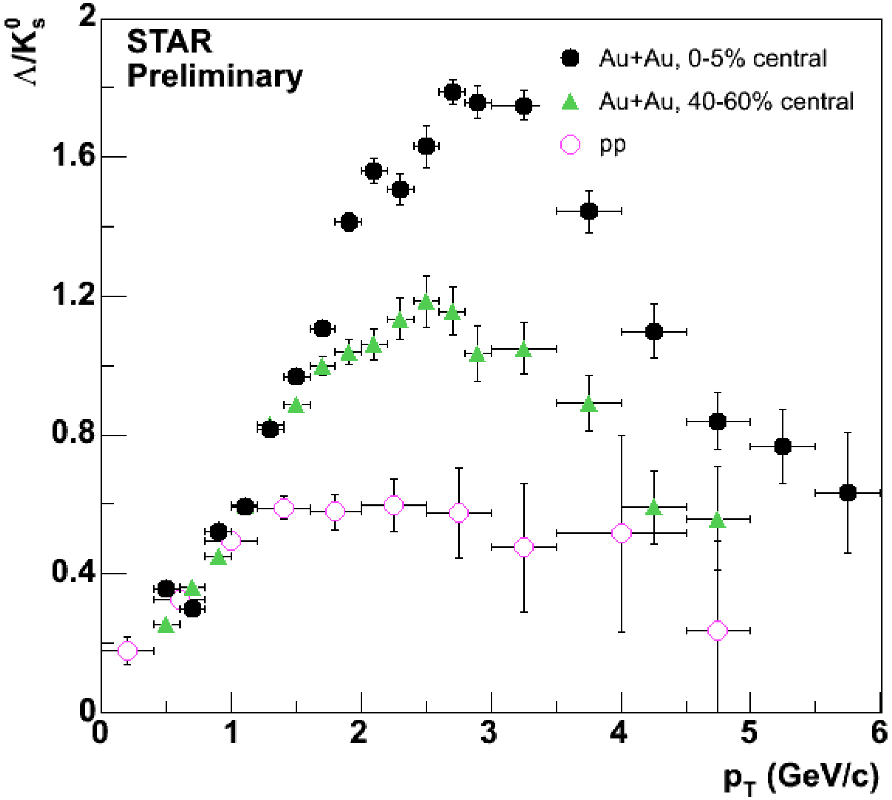
Find: *baryons* not suppressed for pt: 2=> 6 GeV, *mesons* are.
Mesons suppressed => "stuff" is *gluonic*.

R_CP↑



p_t (GeV)=>

Baryon “*Bump*” at p_t: 2 => 6 GeV



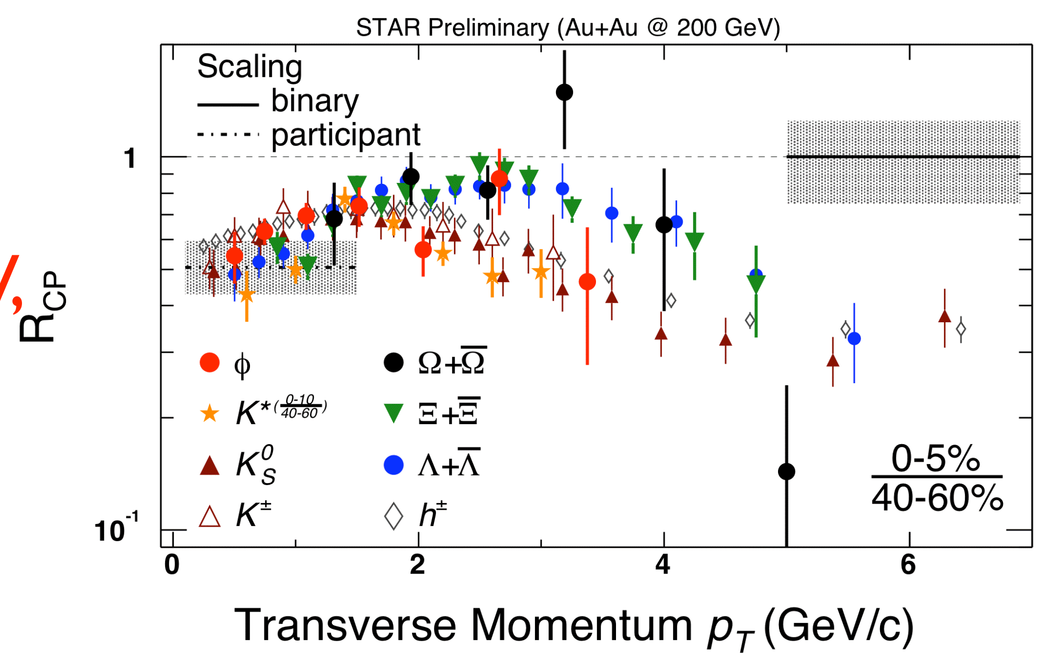
Central AA: *baryon “bump” at p_t: 2 => 6 GeV*

Baryon/meson ratio enhanced by ~3 in central AA vs pp. First seen in p/π.

<= Λ/K ratio: bump peaks at ~ 3 GeV.

Above p_t = 6 GeV, ratios like pp.

R_CP vs particle species =>



All particles suppressed > 6 GeV, R_CP ~ 0.2.

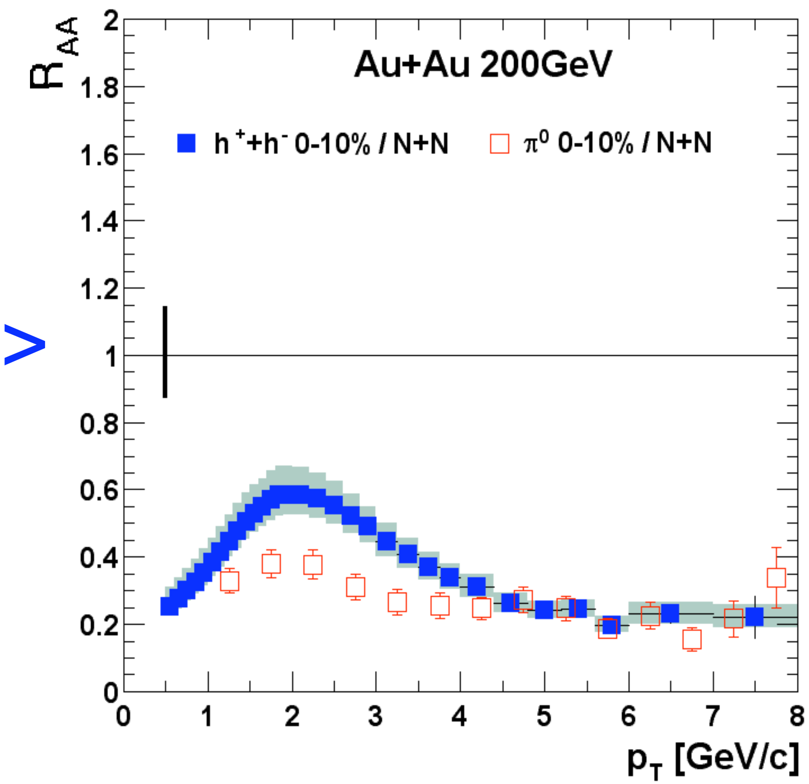
=> *Gluon “stuff”* supp.’s mesons, generates baryon “bump”

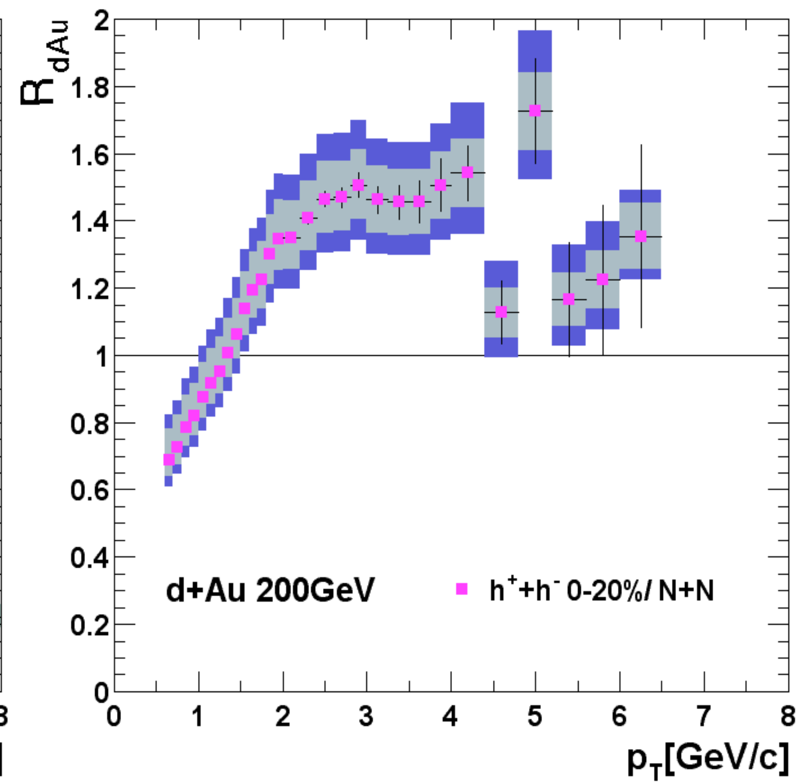
R_AA *Final* State Effect: *NOT* seen in R_dA

Look at R_dA, analogous ratio in dA collisions @ *central rapidity (y=0):*
find "Cronin" enhancement in dA, vs suppression in AA.

Color Glass (initial state effect) predicted suppression in dA, *not* seen.

AA=>





<=dA

Suppression in AA ↑
R_AA ~ 0.4 @ 3 GeV

Enhancement in dA ↑
R_dA ~ 1.4 @ 3 GeV

Where to find the Color Glass: dA, by the *proton*

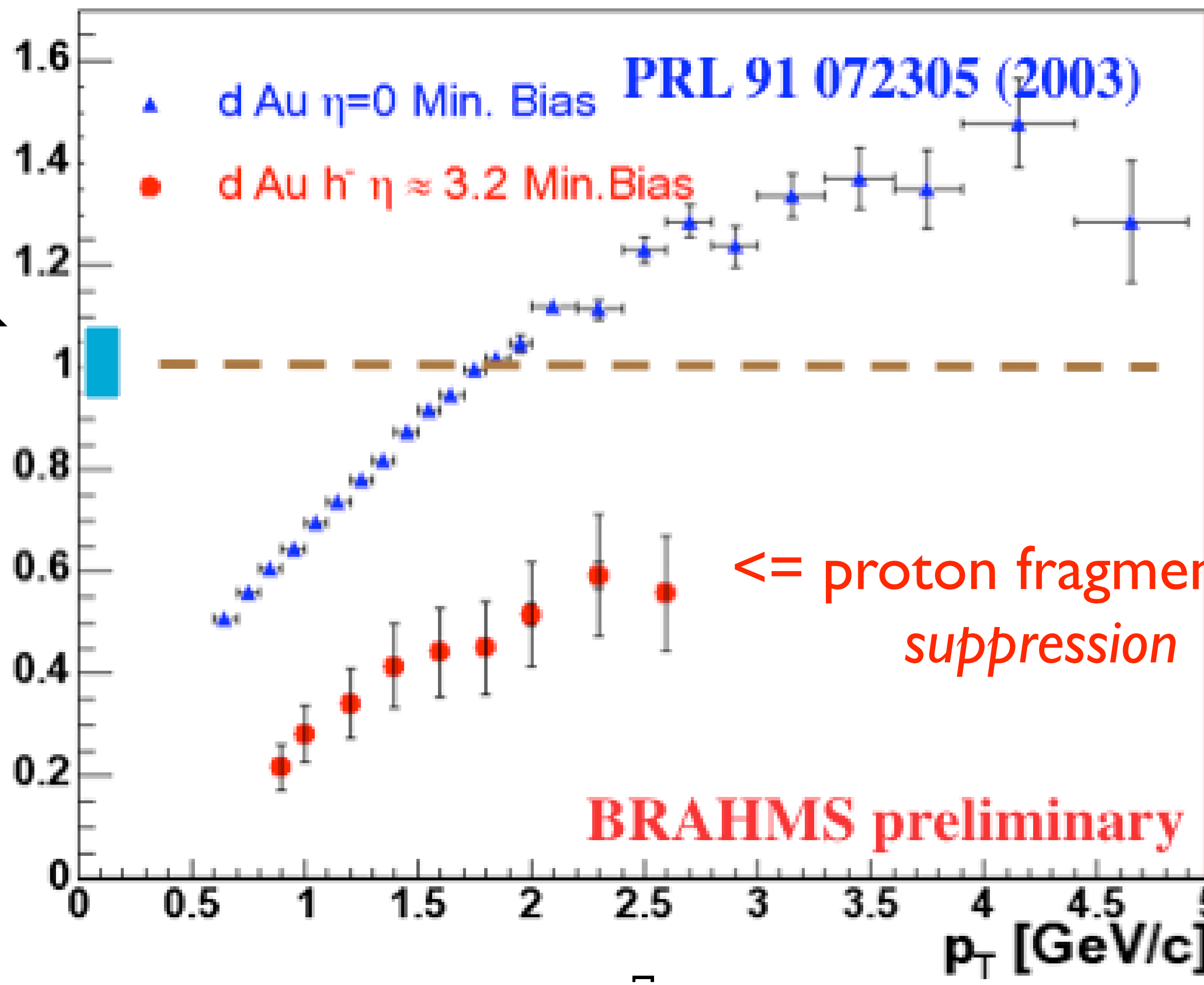
dA: fragmentation region of nucleus tells one about *final* state effects.

frag. region of *proton:* in the proton rest frame, feels the large color charge of the incident nucleus => sensitive to *initial* state effects:

= *the* place to find the Color Glass (Dumitru, Gelis, Jalilian-Marian)

BRAHMS: in dA, *enhancement* @ y=0, *suppression* @ proton frag. region.

R_dA↑



<= central rapidity: *enhancement*

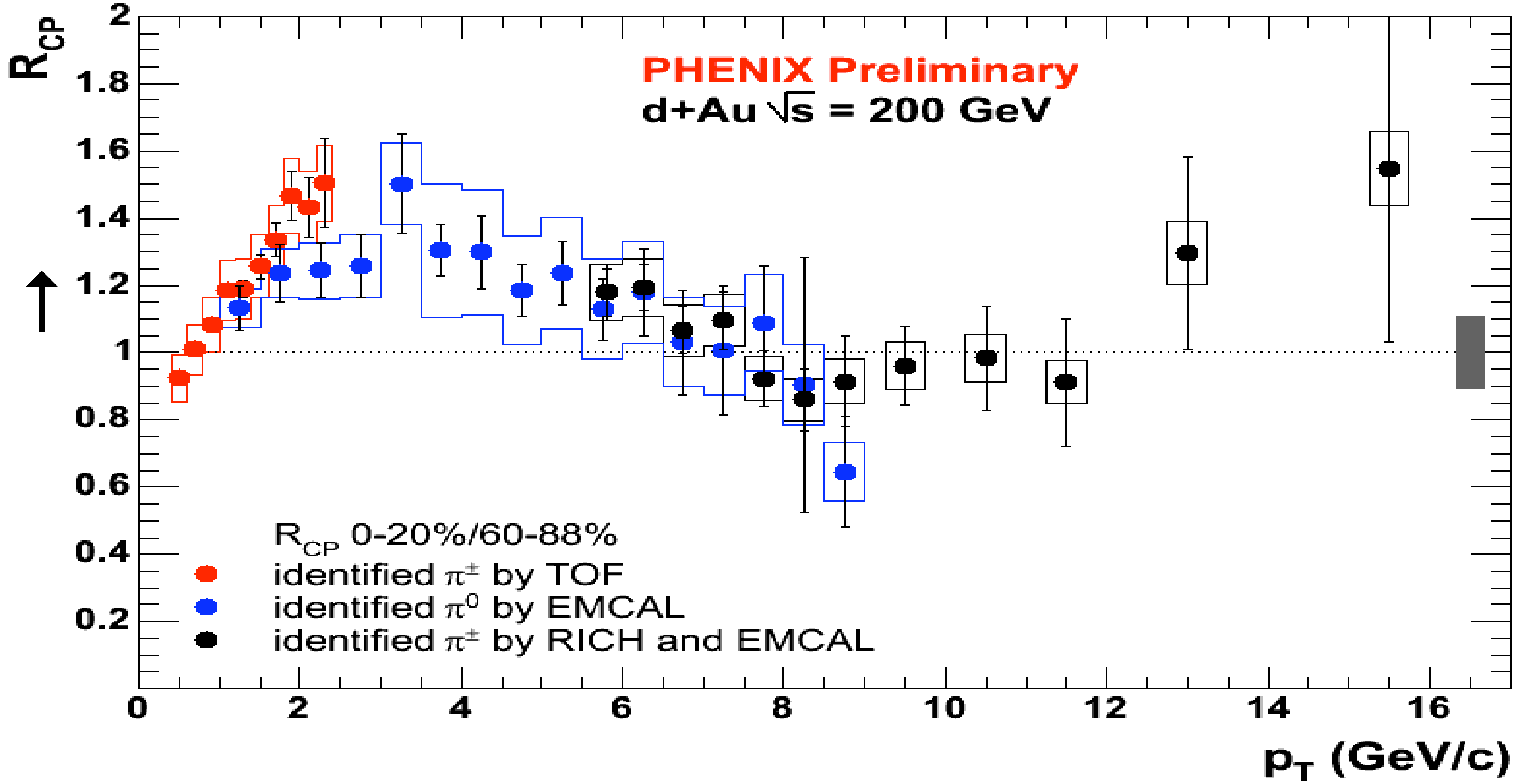
<= proton fragmentation region: *suppression*

dA: No “Cronin” Enhancement at High p_t

At high p_t, *all* R’s (R_AA & R_CP) should go to one.

In dA, seen in R_CP for p_t ~ 8 GeV.

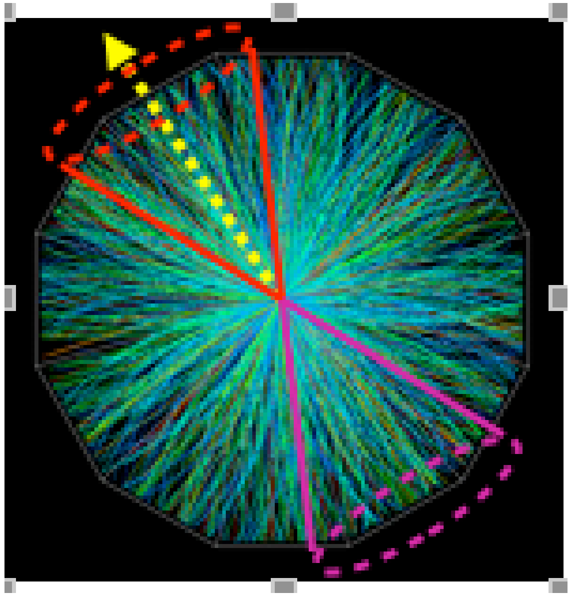
R_CP ↑



p_t=>

At what p_t does R_AA => 1? > 10 GeV!

The "Tail" of the Unicorn: Central AA "*Eats*" Jets



In pp collisions at √s = 130, 200 GeV, clearly see "jets": high energy quarks (& gluons) in each event.

<= "jet" in AA: cannot see on an event by event basis.

In AA, construct statistical measure: trigger on *hard* particle in one direction, look for for *associated* particle in the backward direction

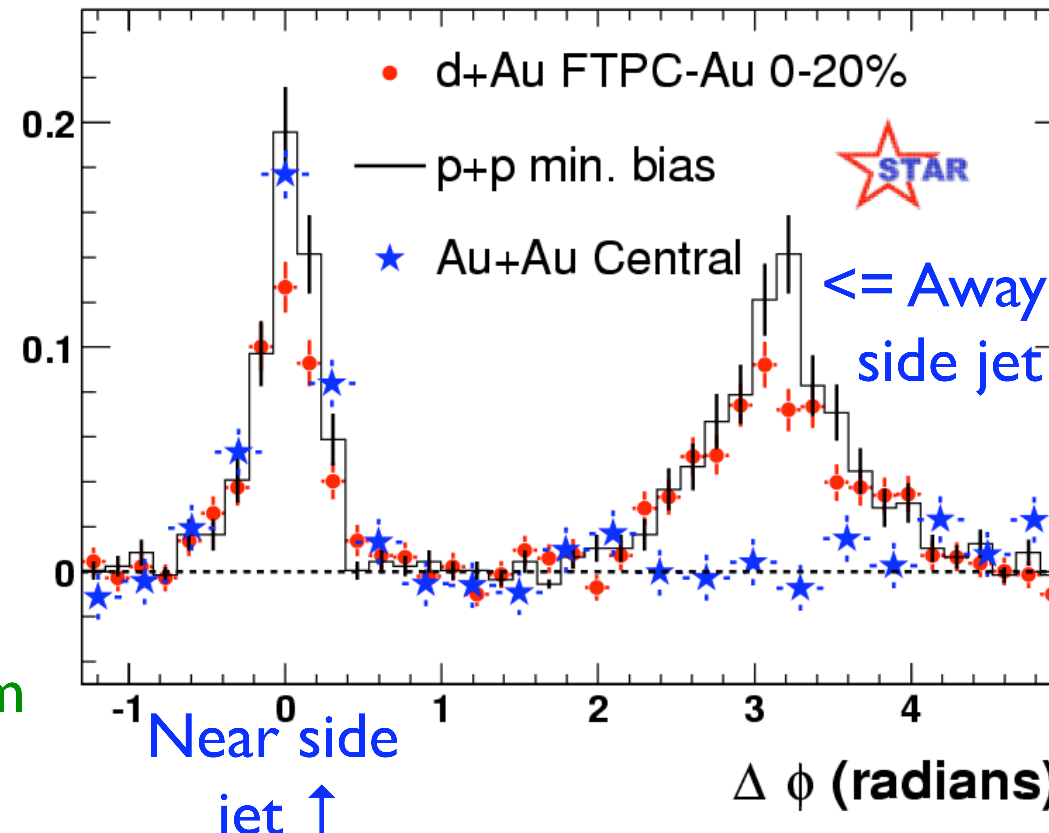
forward: 6>p_t>4 GeV Adams *et al.*, Phys. Rev. Let. 91 (2003)

back: p_t> 2

In pp & dA, *clearly* see "backward" peak in angular correlation => associated jet.

In central AA, backward peak is *gone: "stuff" in AA "eats" jets.*

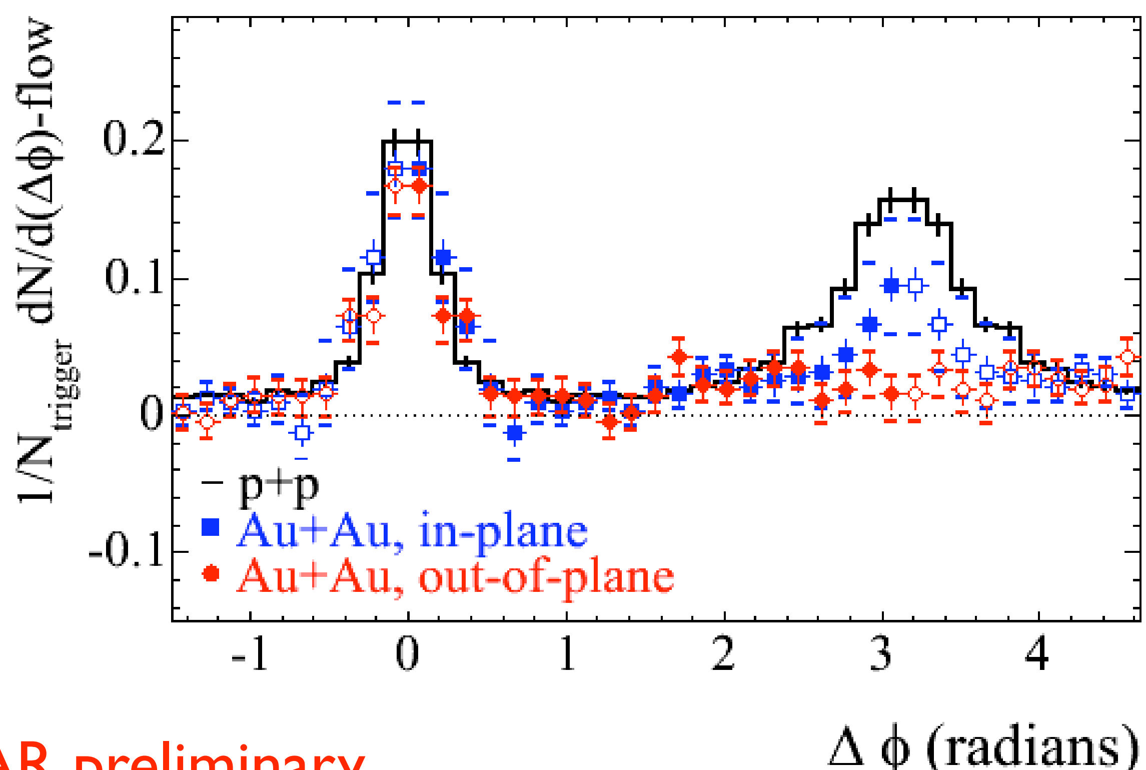
Central AA *really* "eats" the jet: essentially *nothing* at *hard* momentum in the backward direction.



Peripherhal Coll.'s: *Geometrical* Test that AA *Eats* Jets

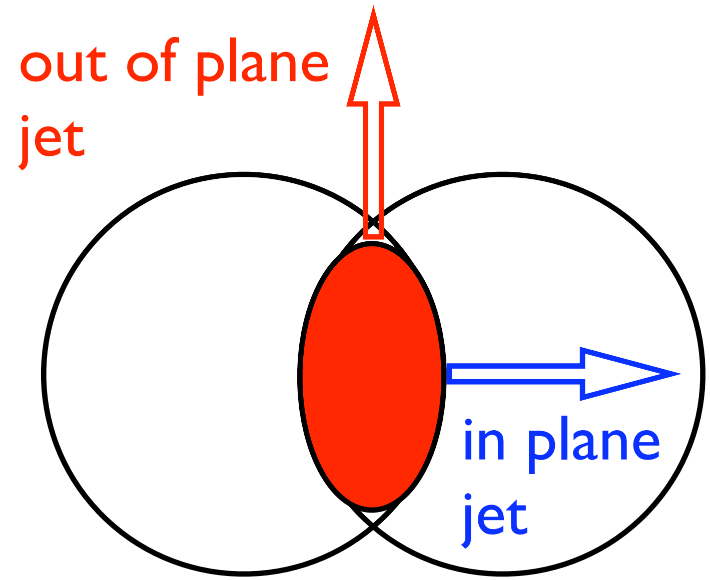
In peripheral collisions, "stuff" forms an "almond"; a jet has to travel farther through the almond, out of the reaction plane, than in the reaction plane.

=> *Geometrical* test that AA *"eats"* jets: backward jet more strongly suppressed out of plane than in plane!



STAR preliminary

Suppression larger out-of-plane



peripheral collision ↑
almond = "stuff"

Where does the Backward Jet go in AA?

As before, trigger on forward jet, 6> p_t > 4 GeV. But look at *all* particles, p_t > .15 GeV, in both forward and backward directions.

In direction opposite to jet, *suppressed* at high p_t (yes), & *enhanced* at low p_t.

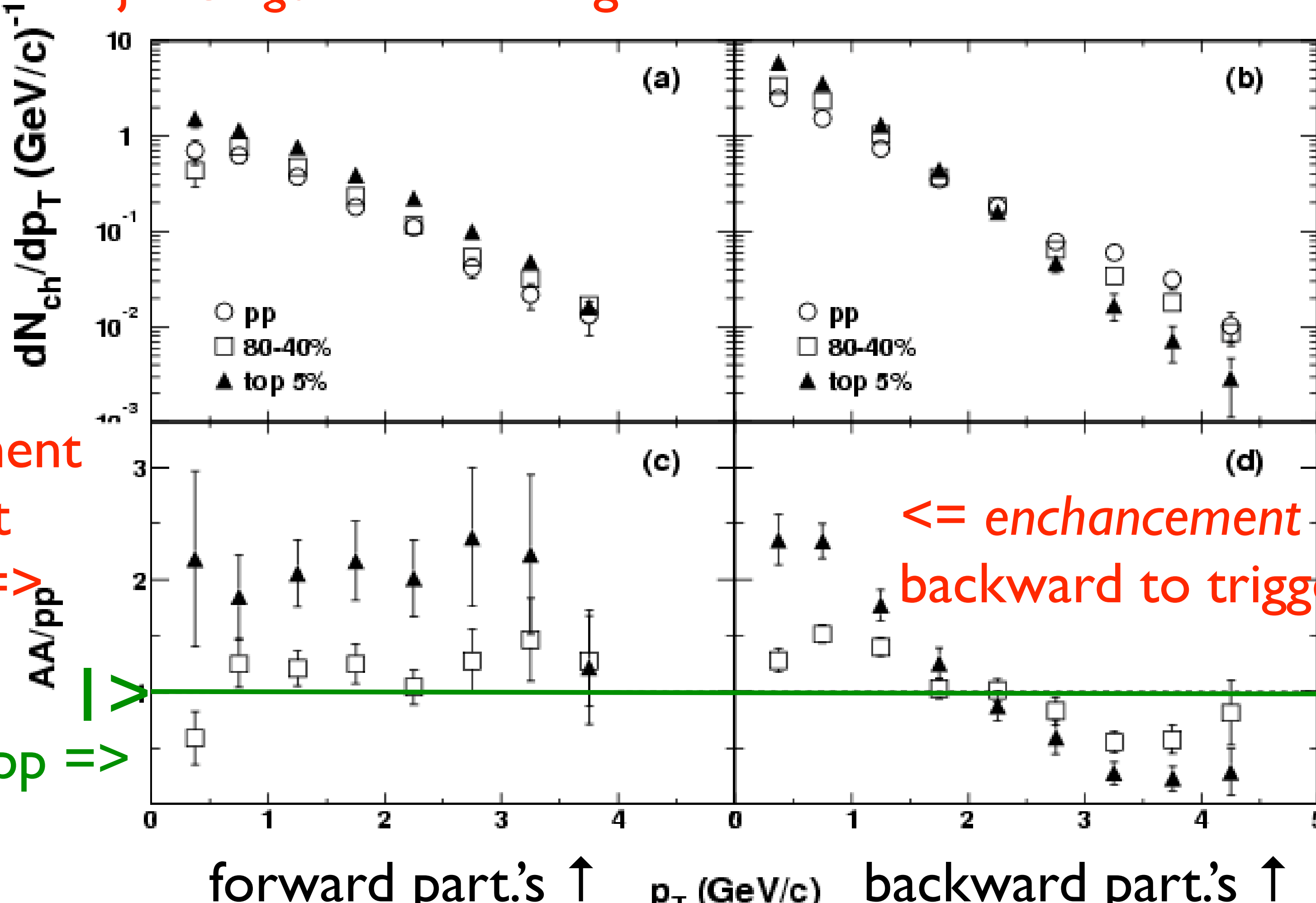
In direction *along* jet, *more* particles at low p_t in central AA than pp.

=> "stuff" in central AA shifts backward jet to *low* momentum,

forward jet *drags* "stuff" along with it!

raw => spectra

STAR prelim.



enhancement at low p_t *along* jet =>

<= *enchancement* at low p_t backward to trigger jet

1 >

AA=pp

ratio, AA/pp =>

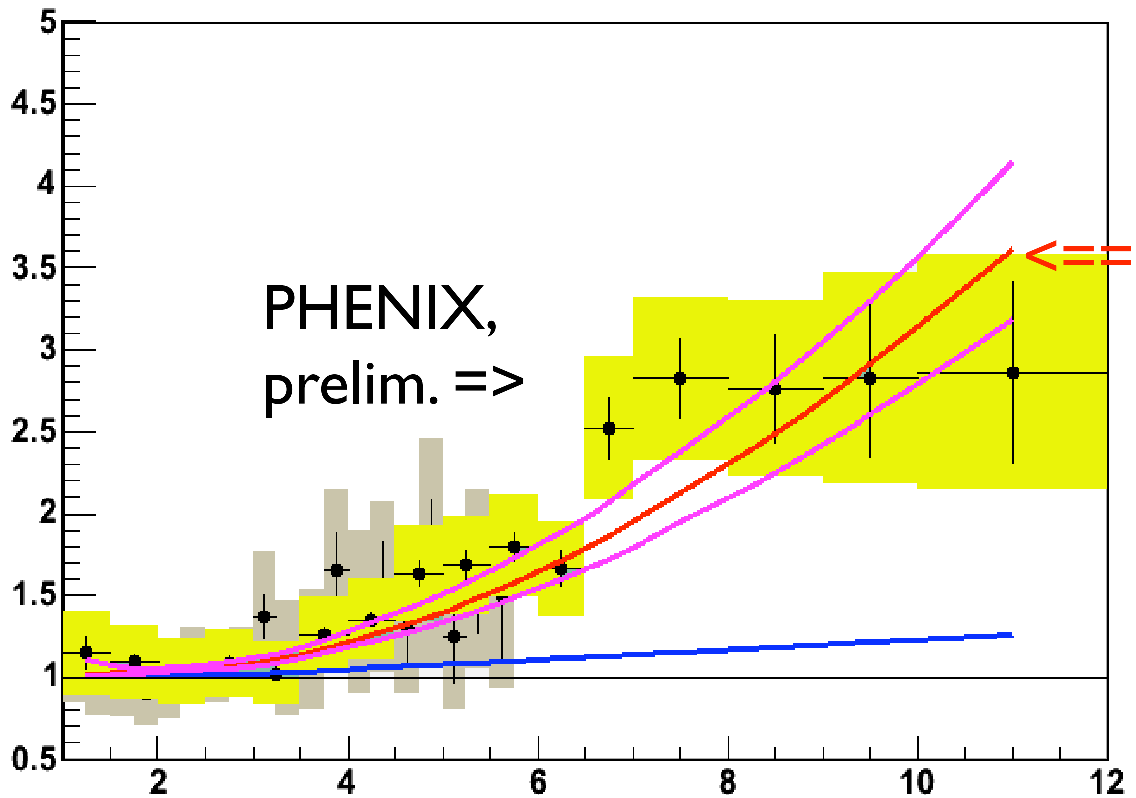
<=*suppression* at high p_t backward

forward part.'s ↑

backward part.'s ↑

Direct Photons Measured

Direct photons: easily escape, so probe initial state. *Without* pion suppression, *very* hard to measure (true at SPS). *With* observed suppression of π^0's, measurable. Reasonable agreement at p_t ~ 10 GeV with Next to Leading Order QCD calculation, = pp times # binary collisions.



<=== NLO QCD,
Vogelsang...

<= signal c/o
π suppression

p_t (GeV)=> 10

Has RHIC found (tamed) the "Unicorn" = QGP?

New final state effects:

R_AA

Suppression of backward jets

Also: new initial state effects,

Color Glass in forward dA

Exp.'y: for the unicorn of central AA, the high p_t "tail" wags the low p_t "body"

HBT? Space-time evolution of the body?

Precise measure of thermal equilibriation?

p_t fluctuations at *low* p_t

Perhaps: it is a different beast....

But its still a *NEW* beast!

"A possible eureka."